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CONTENTS

Geochemical Prospecting Investigations in the Northern Rhodesian Copperbelt ..... *J. S. Tooms and John S. Webb* 815

Minor Elements in a Metasomatic Zone Related to a Copper-Bearing Pyrite Deposit ..... *Yoshimasu Kuroda* 847

A Comparison of Analytical Methods Used in Geochemical Prospecting for Copper ..... *L. C. Huff, T. G. Lovering, H. W. Lakin and A. T. Myers* 855

Bedded Pyrite and Micro-Organisms from the Mount Isa Shale ..... *L. G. Love and D. O. Zimmerman* 875

Some Aspects of Archean Structure and Mineralization ..... *A. M. Goodwin* 897

Geology and Origin of Mineralized Breccia Pipes in Copper Basin, Arizona ..... *W. P. Johnston and J. David Lowell* 916

Beryllium-Bearing Tuff in the Thomas Range, Juab County, Utah ..... *Mortimer H. Staatz and Wallace R. Griffitts* 941

A Syngenetic Copper Deposit of Recent Age ..... *D. C. Fraser* 951

Studies On the Oxidation of Magnetite ..... *K. V. G. K. Gokhale* 963

Bauxite in Sarawak ..... *E. B. Wolfenden* 972

Scientific Communications:

Modified Field Method for the Determination of Nickel in the Presence of Copper ..... *V. G. Hill and A. C. Ellington* 982

A Short Review of Peru's Mineral Resources ..... *W. C. Stoll* 985

An Unusual Occurrence of Molybdenite, In a Manganese Mine, In Tailevu Province, Fiji ..... *M. J. Rickard* 991

Discussions:

Conditions for Ilmenite Alteration ..... *Langtry E. Lynd* 994

Kolar Gold Field, India ..... *T. Pryor* 995

Postdepositional Alteration of Sandstone Minerals Under Acidic Reducing Conditions: A Factor in the Interpretation of Sandstone Texture ..... *B. K. Holdsworth* 996

Iron Formations in the Southeastern States ..... *Virgil I. Mann* 997

Reviews:

Geology of Ore Deposits (Geologiya Rudnykh Mestorozhdenii (Vol. 1, No. 5) ..... *Eugene A. Alexandrov* 1001

Short Reviews of Recent Russian Books ..... *C. F. Davidson* 1006

Die Geologie Mittelamerikas (R. Weyl) ..... *Ervin G. Otvos* 1007

Energy in the American Economy, 1850–1875 (Schurr and Netschert) 1008

Grundlagen der Angewandten Geophysik fur Geologen (Hermann Reich) 1009

Geologie Stratigraphique (Maurice Gignoux) 1009

Books Received ..... *Eric S. Cheney and Roger L. Ames* 1010

Scientific Notes and News 1015

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GEOCHEMICAL PROSPECTING INVESTIGATIONS IN THE NORTHERN RHODESIAN COPPERBELT

J. S. TOOMS AND JOHN S. WEBB

(WITH ANALYTICAL ASSISTANCE BY MARGARET A. GILBERT)

ABSTRACT

Studies in the Northern Rhodesian Copperbelt have shown that the presence of copper/cobalt ore deposits beneath the thick overburden can be detected by the analysis of near-surface samples of the freely drained lateritic and seasonal swamp soils. Total copper and cobalt anomalies related to mineralization have a considerable lateral extent and are normally extended asymmetrically downslope from the suboutcrop.

Dispersion of the copper and cobalt is dominantly saline and the geometry of the anomalies is closely related to the direction of groundwater movement which, locally, may be contrary to the surface topography. Ore metals moving in solution are fixed in the soil by precipitation with sesquioxides and by exchange reactions with clay minerals, manganese wad and organic matter. Anomalous metal in the freely drained soil horizons above the maximum level of the water table is considered to have been transported from the deeper horizons to surface by the vegetation. The sharpness of the anomaly peak over the ore horizon increases with depth, particularly in the freely drained lateritic soil.

In the lateritic soil cold extractable copper anomalies, where detected, are of considerably smaller lateral extent and magnitude than the total copper anomalies. By contrast, cold extractable anomalies of a width comparable or greater than the total copper anomalies were detected in the poorly drained seasonal swamp soil.

Within the seasonal swamps the ratio of cold extractable: total copper is related to the origin of the metal, being higher in seepage anomalies derived from metal rich groundwater, than in soil containing residual metal from an underlying orebody.

The magnitude and extent of the copper/cobalt anomalies is related to the lithology and permeability of the host and wall rocks, the soil type, topography and the ore grade. Relatively constant conditions of geology, pedology and topography are encountered on the Copperbelt

over distances of some miles and in these circumstances the magnitude of anomalies in the freely drained soils reflect the width and grade of the bedrock mineralization.

DESPITE the intensive exploration programs carried out in the Northern Rhodesian Copperbelt over the past forty years or so, considerable areas of potentially mineralized ground remain, where characteristic deep weathering and persistent overburden present considerable difficulties to conventional geological prospecting. Furthermore, although some assistance can be received from self-potential surveys, the nature of the deposits and the circumstances under which they occur are not well suited to current geophysical methods. The application of geochemical techniques, however, offers greater promise under the prevailing conditions.

The first experimental geochemical work in the Copperbelt was undertaken in 1952 by Rhodesian Selection Trust (Services) Ltd., who, after unsuccessful attempts to use the dithizone test for copper in soils, developed by the U. S. Geological Survey, adapted Short's microchemical methods of mineral identification to the semiquantitative estimation of metals in soil and weathered rock. Microchemical tests for copper, cobalt, nickel and zinc were carried out on the concentrate obtained by panning large samples, weighing 4 to 6 lbs., collected from termitaries, prospecting pits and weathered outcrops. The procedures were relatively tedious and, although anomalous metal contents could be detected in samples collected in the vicinity of mineralization, the results often tended to be grossly erratic. At about the same time, independent experiments were also carried out by G. Woodward (then with Roan Antelope Mines Ltd.) who adapted the classical sodium diethyldithio-carbamate test for copper to the analysis of small soil samples collected from depths of 4 to 8 feet by means of an auger. These experiments yielded promising results but the work was not continued.

In 1953, by arrangement with R.S.T. (Services) Ltd., the authors began a detailed investigation with a view to (a) demonstrating the existence of near-surface soil anomalies related to sub-outcropping mineralization, (b) establishing appropriate field techniques for their detection, and (c) determining the more important factors that might influence the interpretation of systematic geochemical data. To these ends, over 3,000 samples were collected from selected areas on the Company's properties at Baluba, Roan Extension, Chibuluma, Musenga and Mufulira. Although a considerable number of analyses were done in the field in order to control the sampling programme, the greater part of the laboratory examination was carried out in London.

Acknowledgments.—The very generous support received from Rhodesian Selection Trust (Services) Ltd., is gratefully acknowledged, as is their permission to publish these results. During the early stages of the work, Mrs. Gilbert was employed under a special Research Grant awarded to J. S. Webb by the Department of Scientific and Industrial Research who also provided a Research Studentship for J. S. Tooms. Latterly, the work has formed part of the activities of the Geochemical Prospecting Research Centre,

Imperial College, which is assisted by substantial grants provided jointly by the Colonial Office and the D.S.I.R.

The authors are also indebted to their colleagues, R. E. Stanton, for analytical assistance, and Professor David Williams, for his continued support and encouragement. In addition, invaluable help and advice was given by many members of the Company's staff, in particular by W. G. Garlick, J. J. Brummer, M. W. Ellis and G. Woodward.

GENERAL DESCRIPTION OF THE AREA

Geology

The Copperbelt, situated in the north-west of Northern Rhodesia (Fig. 1), is underlain by an Archaen Basement Complex of highly metamorphosed

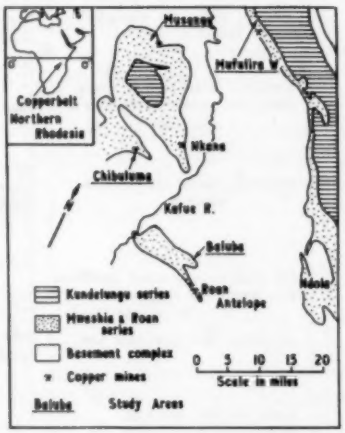

FIG. 1. Map showing location of study areas in the Copperbelt, Northern Rhodesia.

schists, gneisses and quartzites comprising the Lufubu and Muva Systems, the former being extensively invaded by granite. In contrast, the sedimentary assemblage of the overlying unconformable Katanga System has generally been subjected to much lower grades of metamorphism and is intruded only by gabbroic rocks. A typical geological succession is shown in Figure 2 but the lithology of the sediments varies markedly from place to place along the strike.

All the known economic deposits occur in the Katanga sediments, except at the Nchanga Mine where locally some mineralization extends a short distance into the weathered skin of the underlying old granite. Only minor copper mineralization is found, sporadically distributed, in the Basement rocks. In each syncline the greater part of the economic mineralization is confined to one horizon, or at most a few neighboring horizons, in the Lower Roan beds. Locally, additional mineralization may also occur at other levels

in the Roan succession. Stratigraphic control is, therefore, generally very pronounced, and the main ore horizon is commonly more or less mineralized throughout its extent, irrespective of lithological variation in the host- and wall-rocks. In the Baluba study area, the ore occurs in an argillaceous horizon interbedded between arenaceous rocks (Fig. 2), in contrast with Chibuluma, Mufulira and Musenga, where the ore horizon is arenaceous and immediately overlain by dolomite or dolomitic shales.

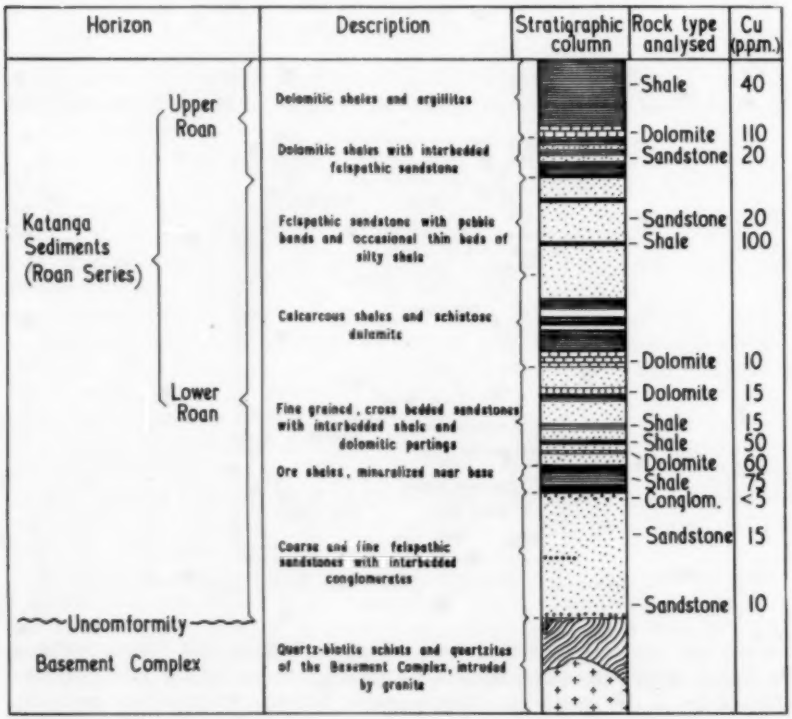

FIG. 2. Variation in the copper content of rocks of the geological succession at Baluba.

The primary ore consists of disseminated pyrite, chalcopyrite, bornite and chalcocite, which show a tendency to zonal arrangement, both laterally and in depth. The ore horizons vary markedly in width and grade but average figures for economic sections range from about 2 to 5 per cent copper over widths of 30 to 50 feet.

Oxidation and leaching extend to depths of 200 to 400 feet or more, depending on the lithology and permeability of the host rocks. As a rule, secondary copper minerals are not conspicuously developed.

Physical Features

The Copperbelt forms part of an extensive peneplain area at an elevation of 4,000 to 4,500 feet, the monotonous topography of which is broken only in a few places by isolated monadocks of older land surfaces. As might be expected, the drainage is mature, with an open dendritic pattern normally unrelated to the underlying geology. The headwaters originate, almost without exception, in shallow depressions on the peneplain surface occupied by seasonal swamps ("headwater dambos"). In plan, headwater dambos are elongated or pan-shaped areas, wherein groundwater enters either over a wide seepage area or from one or more springs, which may dry up completely during the dry season.

Characteristically, the dominant vegetation of dambos is tall grass. With minor exceptions, thin forest cover is confined to the interfluve areas of free drainage where the groundwater lies at about 6 to 20 feet below surface.

The seasonal nature of the climate naturally exerts a considerable influence on the vegetation, fluctuation in the ground-water level, surface drainage and soil development. However, the deep oxidation of the mineralization, which consistently extends for some several hundreds of feet below the present groundwater level, is more probably related to past variations in the climate, and evidence of previous pluvial and arid climate episodes has, in fact, been observed in Northern Rhodesia and surrounding territories.

Overburden

By virtue of the deep weathering and low relief, outcrops are rare and the solid geology is nearly everywhere concealed beneath a thick blanket of overburden which may be up to 60 feet or more deep. Prolonged exposure of the relatively stable land surface has resulted in the development of mature soil profiles that fall into two main classes, depending on the internal drainage conditions within the overburden. Soil types characteristic of free-drainage occupy the interfluves and cover more than 85 per cent of the total area, while poorly-drained soils are confined chiefly to the dambos.

Freely-drained Soils.—The typical profile is composed of three principal soil horizons, designated A, B and C, within which a number of sub-horizons may be recognized. It will be appreciated that the generalized profile illustrated in Figure 3 is not always fully developed.

Briefly, the A horizon is perennially freely drained and consists of light yellow-brown to red-brown sandy loam essentially devoid of rock fragments or other rubble; the top few inches are generally more gray in color, due to the presence of a little organic matter. The greater part of the underlying B, or laterite, horizon is situated immediately above the highest level attained by the water table and is also characterized by predominantly oxidizing conditions. This horizon is composed of numerous dark red to black nodular concretions of sesquioxides up to about ¼-in. in diameter set in a red-brown sandy loam matrix. The nodules are originally quite soft but become progressively harder with increasing desiccation towards the top of the horizon (in the event of more or less complete exposure to the atmosphere by erosion of

the A horizon, the entire B horizon may become indurated into tough cellular laterite). The contact with the A horizon is generally sharp and marked by a "stone-line" of fragmented vein quartz with some bedrock rubble. The contact between the B and the underlying C horizon is gradational and straddles the upper limit of seasonal groundwater fluctuation. Unlike the A and B horizons, where predominantly oxidizing conditions prevail, the C horizon is therefore subject to alternating oxidation and reduction, which produces a characteristic red-brown (ferric iron) mottling in a pallid "matrix" of soft, highly decomposed rock. The intensity of mottling decreases with depth and dies out on approaching the lowest level reached by the water table.

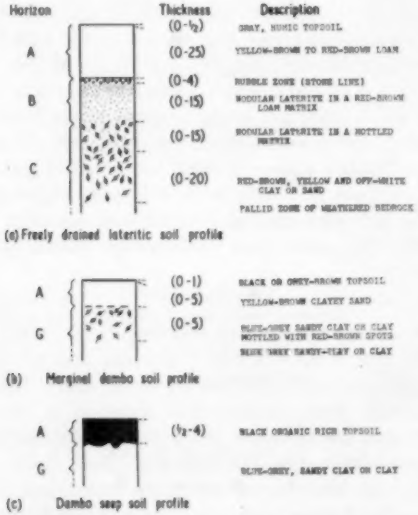

FIG. 3. Diagrammatic soil profiles typical of the Copperbelt.

The common presence of palimpsest rock structures and essentially undisturbed quartz veins testify to the residual origin of the B and C horizons. The A horizon, on the other hand, is composed of homogeneous unconsolidated material except for a very few traces of rock structure immediately above the B horizon. More general evidence for the residual origin of the A horizon is given by the higher clay/sand ratios found over shale as compared to arenaceous and granite bedrock (Table 1), and by a degree of relationship between (i) the color of the subsoil and the iron content of the parent material and (ii) the copper contents of the subsoil and the underlying bedrock (see later). Homogenization of the A horizon is undoubtedly aided by certain species of termites as witnessed by their large conical termitaries, each containing some hundreds of tons of material, which are distributed throughout freely drained areas at an average population density of 1 per

acre. It is believed that, during the course of homogenization, rubble fragments in the subsoil tend to settle and accumulate, forming the "stone-line" at the top of the B horizon.

It must be stressed that the foregoing description of the freely-drained profile is strictly generalized. Local exceptions and modifications are common, especially towards the margins of dambos, where erosion may result in truncated profiles to the extent that the B horizon may be exposed as an outcrop of indurated cellular laterite on the surrounding slopes. Under these circumstances, the relic freely-drained soil horizons bear little or no relation to the changed groundwater levels, which superimpose their own characteristic soil types on the remains of the old profile. There is thus a variable transition from the freely-drained soils on the higher ground to the poorly-drained soils of the dambos.

TABLE 1

AVERAGE CLAY AND SAND CONTENTS AND THE RATIO OF CLAY TO SAND IN THE A HORIZON OVER DIFFERENT BEDROCK

Bedrock	Clay %	Sand %	Clay/Sand × 100
Granite	28	65	50
Basement Complex	26	69	39
Sandstones	31	65	50
Shales	40	55	73
Shales	41	52	78
Dolomitic Shales	42	54	77

Poorly-drained Soils.—Impeded drainage and predominant reducing conditions throughout the profile are responsible for the characteristic glei soils developed in those dambos that are more or less waterlogged for the greater part of the year. Only two principal horizons are developed, referred to as A and G respectively. Where the profile is perennially waterlogged, the A horizon is black, organic-rich, and lies directly on the pale gray-blue sand or clay comprising the G horizon. Towards the dambo margins and throughout those dambos that dry out at the surface for part of the year, the A horizon becomes gray or even yellow-brown in color, consequent on more ready oxidation of the organic carbon and ferrous iron. Seasonal oxidation of ferrous iron also results in the development of red-brown spots and mottling in the upper part of the G horizon. The depth of the A horizon is variable but rarely exceeds 1 to 2 feet; it is not possible to determine the thickness of the G horizon on account of the high water table, which usually stands within 4 feet of the surface, even at the driest time of the year.

It is evident that dambos are a dynamic land form, sometimes retreating but usually advancing at the expense of freely-drained soils. This is shown by changes in the boundaries of individual dambos as seen in series of air photographs of the same areas, taken over a period of years (M. W. Ellis pers. comm.). Additional evidence is given by the isolation, within dambos, of large termitaries composed of freely-drained soil material (the character-

istic termitary found on gray, marginal dambo soil, is dome shaped and stands only about 2 feet high). Relic indurated laterite may also be encountered within the dambo profile, either as fractured blocks or as a warped continuation of the B horizon in the adjoining freely drained soil. According to the level of erosion, therefore, the parent material of dambo soils will include A, B and/or C horizons of original freely-drained profiles which, as previously shown, are derived from the underlying bedrock. However, the dambos must also receive some transported material by erosion of the surrounding interfluves. The amount of such transported material, relative to that of residual origin, will be greatest at the surface and vary in thickness from place to place.

TECHNIQUE

Sampling

For systematic soil traversing, "spot" samples weighing about 100 grams were collected at 18 inches depth from shallow pits dug with an African hoe. Soil profiles, on the other hand, were channel sampled in detail to the dry-season groundwater level, which often lies 40 to 60 feet from surface. Samples below water level in swampy soils were taken by means of a wood-auger after first opening up a hole to the required depth with a crowbar. All samples were collected and sun dried in special kraft paper envelopes.

Analysis

For routine purposes the soil structure is broken up by lightly grinding the sample in a porcelain pestle-and-mortar. The sample is then sieved, usually to 80-mesh.[1]

Total Copper.—For the purposes of this paper, total copper is defined as that proportion of the metal content that is extracted by fusing the sieved sample with potassium bisulphate and leaching the melt with dilute acid (17). In practice, this method of sample attack releases 95 to 98 per cent of the copper; the 25 per cent nitric acid digestion is not satisfactory for red tropical soils, since it may give very erratic, low extractions of the order of 30 to 60 per cent in the case of copper and zinc.

For the majority of samples the metal contents of the bisulphate leachates were determined by the dithizone procedure described by Bloom & Crowe (3). Latterly, determinations have been made using 5 ml of 10% aqueous citrate buffer in lieu of adjusting the pH by titration and benzene or toluene have been used as the solvent for dithizone.

The diquinolyl total copper test (2) also gives satisfactory results on Rhodesian samples. Although diquinolyl is a more stable and more specific reagent than dithizone, the writers have experienced no difficulty in using the latter provided the solvent is pure and the reagent is shielded from sunlight.

[1] Unless stated otherwise all soil determinations were carried out on the minus 80-mesh fraction.

Some samples were analyzed using a chromatographic method for copper, cobalt and nickel (12). However, more satisfactory results were obtained using the colorimetric methods, particularly at low concentration levels.

Cold-extractable Copper.—The term "cold-extractable copper" (abbreviated for convenience to "cxCu") is used here to refer to that part of the total copper content which is soluble in the cold when the sample is shaken with the citrate extractant used in this test. Initially, cold-extractable copper determinations were made using the dithizone-white spirit test described in detail by Holman (11). Subsequently a modified test was introduced that employed benzene as the dithizone solvent (17). The reaction time (1–2 mins.) using benzene is somewhat longer than with white spirit but benzene of the required purity is more readily available in Rhodesia.

The diquinolyl cold extractable copper test (5) was found to give erratic low results probably due to adsorption of the metal complex by the sample (R. E. Stanton pers. comm.).

Total Cobalt.—A few cobalt determinations were carried out using the method described by Almond (1). This method has a greater sensitivity and greater accuracy in the low concentration range than chromatography (see above) but is relatively tedious.

Recently, a new field test for cobalt has been developed in the Chemistry Department of Imperial College (14). Final development work is not yet complete but the procedure, which uses KCNS and tri-*n*-butylamine promises to give good sensitivity combined with greatly increased productivity.

RESULTS

The distribution of copper and cobalt in the soil was determined at several mineralized localities including Baluba, Chibuluma, Musenga and Mufulira West (Fig. 1). In addition, samples were collected in unmineralized areas to establish the normal or background metal contents. A total of over 3,000 samples was collected and analyzed for total copper. The majority were also examined for cold-extractable copper and a few for total cobalt. In all, some 6,000 analyses were carried out. Preliminary examinations had shown that the minus 80-mesh fraction of the soil at 12 to 18 inches from surface was adequate to detect anomalies related to underlying deposits (16, 18). Except when stated otherwise, the results given below refer to samples of this specification, which are also the most convenient for routine prospecting purposes. Deeper samples and an appreciation of certain factors affecting metal dispersion are also necessary for the reliable interpretation of near-surface anomalies. These aspects are considered in the section following presentation of the data obtained on near-surface samples.

Metal Distribution in Near-surface Soils

Background Metal Content.—Data concerning the background content of copper, cobalt, and nickel in freely-drained soils derived from presumably unmineralized rock are presented in Table 2. These results show a considerable variation in metal content related to differences in the underlying

rock. In particular, relatively high copper, cobalt, and nickel contents were observed in samples collected over gabbroic rocks and in some areas underlain by Lufubu schists. Unfortunately, it was not possible to obtain soil samples over barren Roan sediments, where the geology was known in detail. However, none of the analyses of the drill core of the fresh rock (Fig. 2) exceed 170 ppm Cu and the average content of 19 samples is only 45 ppm. Although some loss of copper would be expected upon weathering, the decrease would probably be relatively slight if one assumes that most of the primary copper occurs as traces in the rock-forming silicates.

Considering the data as a whole, but excluding gabbroic bedrock, the median background content of near-surface freely drained soil is 45 ppm. Cu. The threshold or upper limit of normal background variation is estimated to be 75 ppm. Corresponding figures for cobalt are a background of 2 ppm and a threshold value of 12 ppm.

TABLE 2

COPPER, COBALT AND NICKEL CONTENTS OF NEAR SURFACE FREELY DRAINED SOILS IN THE STUDY AREAS

Bedrock	No. Samples	Total copper, ppm		cxCu		Co		Ni		Mean Co/Ni ratio
		Range	Mean	Range	Mean	Range	Mean	Range	Mean	
Roan Sediments (unmineralized)	21	15–70	40	1.0–6.8	2.7	<1–15	≤2.5	4–28	10	0.25
Basement complex	18	10–85	50	0.6–6.6	2.7	<1–12	≤1.5	4–26	9.5	0.16
Granite	6	10–50	30	0.4–2.0	1.0	<1	<1	<2–6	≤3	0.3
Gabbro	2	135–170	150	3.0–5.0	4.0		105	120–200	160	0.6
Mineralized shales	15		450		13.0		50		15	3.0
do. sandstones	5		130		4.0		30		7	4.0

The high copper and cobalt contents of freely drained soils over barren gabbroic rocks and Lufubu schists may be equivalent, under certain circumstances, to anomalies associated with significant mineralization in Roan sediments (see later). However, in most cases, the nature of the metal source can be distinguished on the basis of the nickel content and the Co : Ni ratio in the soil. If the source is mineralization in the Roan series, nickel will usually be less than 20 ppm, accompanied by a Co : Ni ratio greater than 1.0; over gabbroic rocks and Lufubu schists on the other hand, the nickel content may range up to 200 ppm and the Co : Ni ratio will be less than 1.0. Preliminary investigations of cold-extractable copper showed that values were liable to be extremely low in freely drained soil, particularly in samples collected at depths of 12 to 18 inches or more. Values are somewhat higher in the surface soil but at the same time are more erratic in their distribution. The data given in Table 2 show the variation to be from 0.4–6.8 ppm cxCu with a mean value of 2.7 ppm; the provisional threshold is of the order of 7.5 ppm cxCu for samples collected at depths of 0 to 12 inches. For samples at 18 inches, the values are normally less than 1 ppm cxCu.

The preceding paragraphs refer only to freely-drained soils. Appreciably higher contents of both total and cold-extractable copper occur in the seasonally waterlogged soils of the dambos in barren areas. Here the normal background for total copper varies from 30–300 ppm; cold-extractable copper usually ranges from 4–20 ppm (17). These wide ranges of metal content are probably related in part to the nature of the poorly drained soils and in part to economically insignificant changes in the metal content of the bedrock underlying the dambo and its catchment area.

Copper Anomalies in Freely-drained Soil Related to Ore in Argillaceous Host Rock.—The Baluba Special Grant provides a typical example of an area where the ore occurs in argillaceous host rocks. The general geology is very similar to that in the vicinity of the Roan Antelope Mine (4, 8). Disseminated ore occurs in a shale horizon near the base of the dominantly arenaceous Roan series. The ore shale itself becomes rather sandy towards the eastern boundary of the Grant. Below the ore horizon, the footwall beds are composed of felspathic sandstones with interbedded conglomerates. Above the ore shales, the series is also dominantly arenaceous but includes

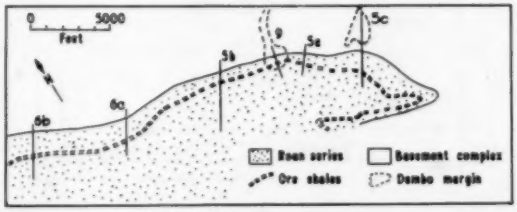

FIG. 4. Location and figure number of selected soil traverses at Baluba.

interbedded shales and dolomites, particularly in the lower part of the succession. The Upper Roan rocks which sub-outcrop in the center of the syncline are argillaceous and dolomitic (Fig. 2).

The Roan sediments at Baluba are almost entirely overlain by freely-drained ground. Only in one part of the area does the sub-outcrop of the Roan sediments pass beneath the poorly-drained soils of a dambo. The topography is flat-lying with exceedingly gentle slopes that generally do not surpass 1°. Rather more definite, but still gentle, gradients of up to 3° occur in the immediate vicinity of the dambos. Despite the peneplain topography, the slight changes in slope are sufficient to cause considerable variation in the form of the anomalies.

Traverse 5a (Fig. 4) crosses the ore shales where the dip is approximately vertical and the average grade in depth exceeds 2.5% Cu over a width of more than 30 feet. The traverse lies close to and sub-parallel to an ill-defined divide between two minor catchment basins on the peneplain surface. Topographic relief is negligible, with only a very gradual slope towards the north at an angle of 25° to the strike direction of the sub-outcrop of the ore. The residual overburden, which is up to 60 feet thick, is a

freely-drained soil with a well differentiated lateritic profile. Analysis of the near-surface soil (Fig. 5a) discloses anomalous copper values that increase gradually from background to about 350 ppm Cu before rising sharply in the vicinity of the ore sub-outcrop to a peak of 700 ppm Cu. The overall width of this anomaly is 1,500 feet, and the values are disposed almost sym-

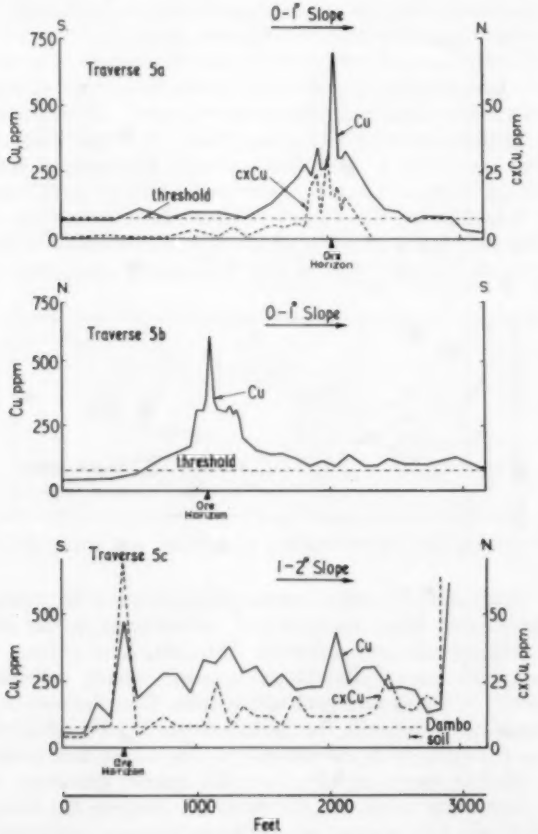

FIG. 5. Anomalies in near-surface soil over economic mineralization at Baluba.

metrically on either side of the ore horizon. There is, therefore, a considerable extension of the anomaly upslope from the sub-outcrop. Analysis of drill core chips (Fig. 2) indicates that the upslope dispersion is entirely secondary, as no primary dispersion is detectable in the bedrock. The foregoing results refer to the distribution of total copper. By contrast the anomaly for cold-extractable copper is much narrower.

Similar bedrock, soil type, and grade and width of ore, occur on the line of Traverse 5b (Fig. 5b). Here, however, the surface is slightly more inclined, although the gradient does not exceed 1°. The ground slopes to the south-west, crossing the geological strike at an angle of approximately 70°. The lower slopes lie on the up-dip side of the ore-body, which is inclined at 85° from the horizontal. The anomaly disclosed on this traverse is over 2,500 feet wide and slightly extended asymmetrically downslope from the ore horizon. However, as on Traverse 5a, there is a considerable extension of the anomaly upslope from the sharp peak values rising to 580

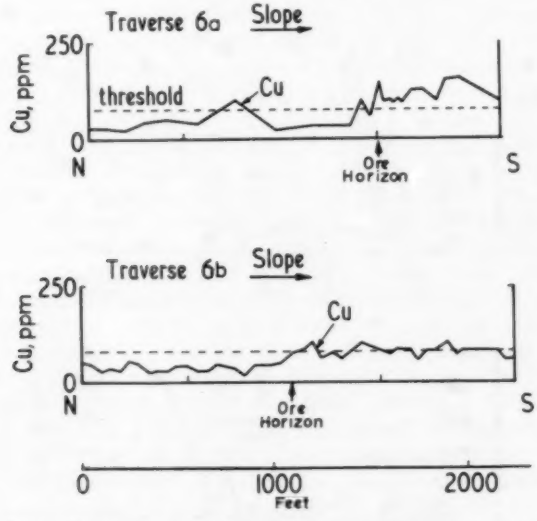

FIG. 6. Anomalies in near-surface soil over sub-economic mineralization at Baluba.

ppm Cu immediately over the sub-outcrop. Again, there is no evidence to suggest that the upslope extension of some 500 feet is related to primary dispersion of metal in the underlying bedrock.

On Traverse 5c, east of Traverse 5a, the general geology is similar, but the ore shales, which are of comparable grade and width, become rather more sandy and dip at a relatively shallow angle to the south-west. The freely-drained surface slopes to the north-east, almost at right angles to the geological strike, its gradient being rather more than 1° on the freely-drained ground beneath which the ore horizon lies, increasing to over 2° as the dambo is approached near the end of the traverse. The copper anomaly is markedly asymmetrical with strongly anomalous values of 200–400 ppm Cu extending over the whole distance of 2,000 feet downslope from the ore to the dambo (Fig. 5c). In this case there is negligible extension of the anomaly on the upslope side of the ore. Furthermore, the anomaly peak

of 400 ppm Cu immediately over the sub-outcrop is not so marked as on the traverses previously described. It is considered that this is due to the more sandy nature of the host rock (see below). The distribution of cold-extractable copper is much more erratic than that of total copper. The anomaly is much suppressed, but the asymmetrical extension downslope in the freely-drained soils is still shown.

Beyond the limits of the freely-drained section of the traverse, copper shows a marked increase in the seasonal waterlogged soils of the dambo, where the maximum content exceeds 2000 ppm Cu (Fig. 7). The content of cold-extractable copper rises even more spectacularly to 780 ppm exCu.

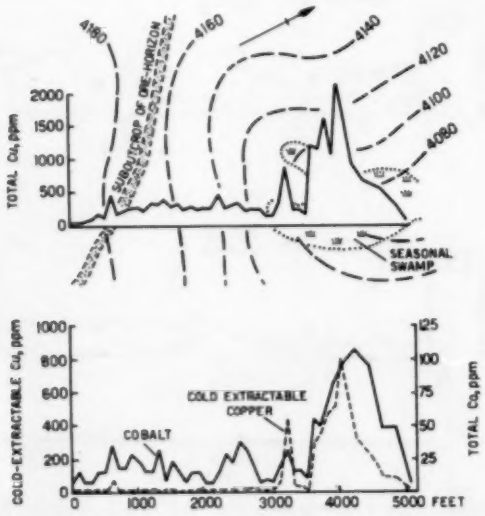

FIG. 7. Accumulation of metal in seepage area soils downslope from the ore horizon at Baluba (Traverse 5c).

Near the dambo margins, however, the metal values are lower than those towards the center of the dambo on the one hand, or in the adjoining freely-drained soil on the other. Marginal soils typically show a profile transitional between the freely-drained and poorly-drained profiles described previously. Discussion of metal distribution in relation to soil type is given later. Suffice to note here that the metal content of the dambo is due to precipitation of copper from groundwaters draining the mineralized ground that lies beneath the freely-drained overburden more than 2,000 feet upslope. Drainage anomalies developed in the dambos at Baluba have been described in more detail elsewhere (17).

Anomalies in Freely-drained Soil Related to Sub-economic Mineralization in Argillaceous Host Rock.—On Traverse 6a the mineralized horizon is considered to contain no more than 2% Cu over a very much reduced width

of 10 feet. In other particulars, the geology and soil type are very similar to those encountered on Traverse 5b. The surface is inclined at an angle of about 1° to the south, crossing the geological strike nearly at right angles. The distribution of copper in the near-surface soil along this traverse shows a relatively feeble anomaly extending asymmetrically downslope. There is negligible dispersion upslope from the mineralized horizon. The maximum copper content is only 170 ppm and, unlike the other traverses previously described, the peak value lies some 300 feet downslope from the sub-outcrop. Similar displacement of the anomaly peak downslope was also observed on Traverse 6b over low-grade mineralization.

Copper Anomalies in Freely-drained Soils over Ore in Arenaceous Host Rock.—The dispersion of copper from arenaceous host rocks was examined at Chibuluma and Musenga (Fig. 1). In both areas mineralization occurs along a relatively short strike length and consequently only a limited study was possible.

On Traverse 11 at Chibuluma (Fig. 11), both the ore horizon and the footwall beds consist of felspathic sandstone. The hanging wall is also arenaceous at the contact but becomes dolomitic within a few feet of the ore. The rock succession is steeply inclined. Although the grain size of the disseminated sulfides is somewhat coarser than in the argillites at Baluba, the mineralogy of the ore is similar at both localities. However, the grade of the Chibuluma mineralization is considerably higher than any encountered at Baluba, and exceeds 5% Cu over a width of more than 40 feet. The overburden is freely-drained and the ground slopes gently at an angle of 1° in a northerly direction across the ore horizon. Despite the higher grade of ore, the anomaly is much smaller than those detected at Baluba (compare Figs. 11 and 5a). On Traverse 11 at Chibuluma the maximum value is only 170 ppm Cu in the near-surface soils immediately over the sub-outcrop of the arenaceous ore horizon. Furthermore, the anomaly shows no marked peak over the ore. There is very little evidence of metal dispersion upslope, and the anomaly shows marked asymmetry in the downslope direction. The full lateral extent of the anomaly could not be determined due to contamination from a mine dump, which affects the metal content of the soil at a distance of 300 feet downslope from the suboutcrop of the ore horizon. Further data obtained by Rhodesian Selection Trust, subsequent to the writers' field work, indicate that this traverse passes through a relatively feeble section of the anomaly. However, the copper content of near-surface soils over the ore further along the strike rises to only a few hundred ppm, which is appreciably lower than that recorded over lower grade mineralization in argillaceous rock at Baluba.

The geology at Musenga is similar to that at Chibuluma, both the ore horizon and footwall beds being arenaceous. The hanging wall, however, is composed of a succession of interbedded sandstone, dolomites and shales overlain by more shales. Due to drag folding the outcrop of the shales is extensive. The mineralized zone is of comparable thickness to that at Chibuluma, but is of lower grade. Work was confined to an area where the ore horizon lies beneath freely-drained lateritic soil. The ground slopes very

gently across the strike towards a dambo which lies 2,000 feet to the southwest. The anomaly in the near-surface soils (Fig. 8) extends for over 2,000 feet downslope from the suboutcrop, attaining maximum values of 150 ppm copper over the shales, as compared to an average content of only 80 ppm over the mineralized sandstone. Drill hole data give no indication of the presence of mineralized ground in the hanging wall shales. It is considered that the high values in the soil over these rocks are due to fixation of copper dispersed in solution from the weathering orebody further upslope. Probably the metal leached in the arenaceous environment of the mineralization was reprecipitated when the groundwater solutions encountered the clay-rich environment of the weathering argillaceous horizons.

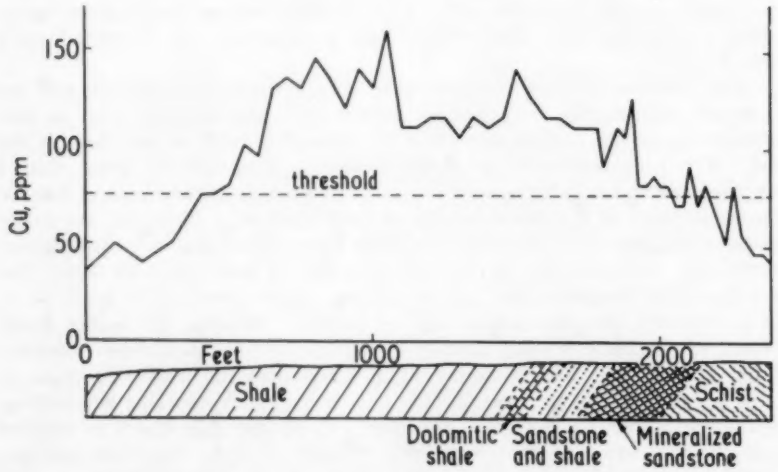

FIG. 8. Illustrating the broad diffuse anomalies commonly observed in residual near-surface soil over ore in arenaceous host rocks, Musenga.

Anomalies in Poorly-drained Dambo Soil.—The bedrock geology along Traverse 9 at Baluba is essentially the same as that along adjoining Traverses 5a and 5b described earlier. The grade of mineralization in the argillaceous host rock is greater than 2 per cent. In contrast with the other traverses, the overburden is a typical dambo soil and predominantly reducing conditions prevail in the organic-rich environment. The ore, however, was previously oxidized and partially leached to an appreciable depth, prior to the advent of dambo conditions. Due to the high water table, which is at or close to surface for much of the year, trees are absent and grasses are the only vegetation. The total copper content of the soil shows a marked increase from 90 to 4,500 ppm Cu on passing downslope across the suboutcrop of the mineralization, and the anomalous values decrease greatly downdrainage (Fig. 9). The drainage train has been described in some detail

elsewhere (17) and will not be considered further here. However, attention is drawn to the trough of low values immediately downslope from the mineralized ground. It is considered that the high values beyond this trough reflect copper precipitated from groundwaters in the main seepage area of the dambo, down-drainage from mineralization. The metal-rich seepage area is, therefore, the commencement of the drainage train proper. Peak values immediately upslope from the trough of low values are believed to be

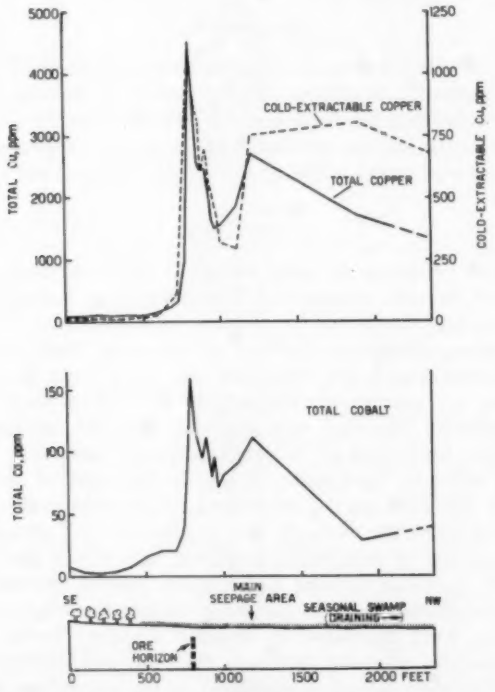

FIG. 9. Copper and cobalt anomalies in poorly drained soil overlying mineralized bedrock.

largely of residual origin and directly related to the underlying orebody. The magnitude of this residual anomaly compared to the low values characteristically found over equivalent mineralization in freely-drained ground, is considered to be due to relatively ineffective leaching of the oxidized ore in the poorly-drained and reducing environment of the dambo.

The distribution of cold-extractable copper closely follows that of total copper but the magnitude of the contrast between anomaly and background is even greater, as shown by the peak value of over 1000 ppm cxCu immediately above the ore, as compared to 12 ppm upslope.

In this dambo, much of the copper in the soil in the immediate vicinity of the ore is probably residual in origin. The proportion of this total copper that is cold extractable is much lower than in the neighboring dambo wherein the copper was precipitated from metal-bearing groundwaters draining ore lying some 2,000 feet upslope (17). The ratio of cold-extractable to total metal may, therefore, be used on occasion to discriminate between residual anomalies related to underlying deposits and seepage anomalies derived from metal-rich groundwaters.

DISCUSSION

Consideration of the data shows that the development of the soil anomalies related to mineralization is influenced by a number of factors, notably topography, soil type, bedrock lithology and the grade of the deposit. An appreciation of these factors and the mechanics of the dispersion process is necessary to the reliable interpretation of the results of geochemical soil surveys.

Topography

Asymmetrical extension of metal values in the downslope direction is a common feature of soil anomalies. The surprising feature in the areas examined is the magnitude and persistence of the downslope extension on quite gentle slopes, commonly inclined at no more than 1–2°. Although mechanical dispersion by sheet wash and soil creep must be a contributory factor, they are not considered adequate in themselves to account for the degree of asymmetry observed, nor can they account for the upslope extensions of values, sometimes for several hundreds of feet.

The major effect of topography in the development of anomalies is believed to be its influence on the movement of groundwaters carrying metal in solution away from the orebody, the gradient of the groundwater table, and thus the direction of flow, being largely a reflection of the surface gradients. However, particularly near topographic divides, groundwater movement will also be affected by other factors, including the relative rate at which the groundwater level fluctuates in adjacent drainage basins. In the flat peneplain topography of the Copperbelt this can result in periodic movements of metal-rich groundwater unrelated to the immediate surface topography. The upslope extension of anomalous metal values forms part of the evidence for concluding that groundwater solutions have played a major role in developing the soil anomalies. This problem is discussed in more detail in a later section of the paper.

Soil Type

Thus far we have been concerned with the distribution of copper in the near-surface soils, at a depth of 0 to 18 inches. However, the metal content shows significant variations within the soil profile as a whole, which are of considerable practical importance. In this respect there is also a very pronounced difference between freely-drained and poorly-drained profiles.

Freely-drained Profiles.—As previously described, the freely-drained soil profile is sub-divided into three major horizons: a sandy or loamy A horizon overlying a nodular, lateritic B horizon, which passes downwards into a mottled C horizon. The latter lies within the zone of seasonal groundwater fluctuation. Although a "stone line" is commonly present at the sharp junc-

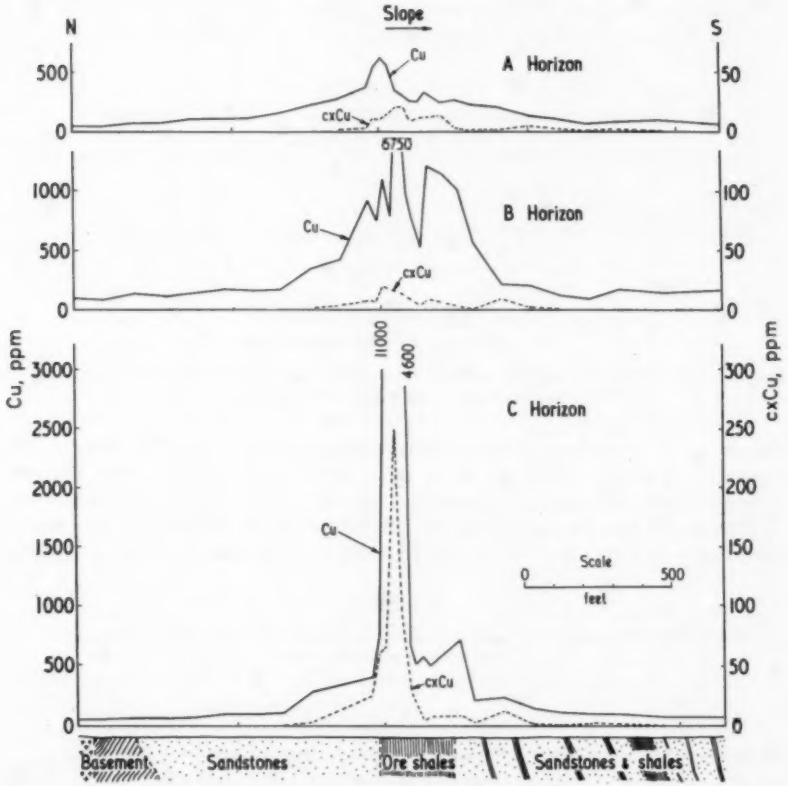

FIG. 10. Variation in copper anomalies in different soil horizons overlying ore in argillaceous host rock, Baluba (Traverse 5a).

tion of the A and B horizons, the essentially residual nature of the entire profile is confirmed by the correlation between the results of mechanical analysis and bedrock lithology (Table 1). The formation of this well differentiated soil profile naturally influences metal dispersion. Typical examples of corresponding anomalies developed in the three major soil horizons are given in Figures 10 and 11. In general, the copper content of the B horizon, both in background and anomalous areas, tends to be higher than in either

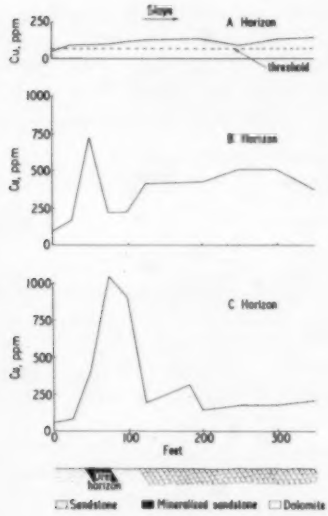

FIG. 11. Variation in copper anomalies in different soil horizons overlying ore in arenaceous host rock, Chibuluma.

the A or C horizons. Furthermore, although the lateral extent of the anomalies is almost the same in all three horizons, it will be noted that the anomaly peak becomes progressively sharper with depth. A comparison of Figures 10 and 11 shows that the magnitude of the differences on passing from the A to the C horizon is much greater over arenaceous host rocks than

TABLE 3

VARIATION IN COPPER CONTENTS ACCORDING TO SIZE FRACTIONS IN FREELY-DRAINED AND POORLY-DRAINED SOILS

Location	Soil Type	Depth	Cu content (ppm)					
			Coarse sand, −20+35 mesh*	Medium sand, −35+80 mesh	Fine sand, −80+135 mesh	Very fine sand, −135+200 mesh	Clay and silt, −200 mesh	−80 mesh
Background	Freely-drained latosol	18″	35	55	45	40	85	45
		18″	65	50	40	45	90	55
Anomaly		18″	70	70	55	95	155	105
		18″	100	95	95	120	190	135
Anomaly	Poorly-drained dambo soil	18″	1,900	2,700	2,500	2,300	3,050	2,450
		18″	2,100	2,000	2,250	4,100	5,000	3,750
		36″	725	725	1,000	1,625	3,200	2,150

* B.S.S. sizes.

over argillites. The tendency of the anomaly peak to become sharper with depth is of considerable value in prospecting. Anomalies disclosed by near-surface sampling may be followed up by deep samples in order to locate the bedrock source with more precision.

Within the A horizon the copper tends to be concentrated in the finer fractions of the soil comprising clay, silt and finely divided sesquioxides (Table 3). The cold-extractable copper content is extremely low except in the first foot of the soil, where a little organic matter is generally present.

TABLE 4

ILLUSTRATING ASSOCIATION OF COPPER WITH IRON AND MANGANESE IN FREELY-DRAINED SOILS

Soil horizon	Copper contents in ppm									
	−80 mesh fraction		Matrix		Ferruginous concretions		Manganiferous wad		Ferruginou mottling	
	Total Cu	cxCu	Total Cu	cxCu	Total Cu	cxCu	Total Cu	cxCu	Total Cu	cxCu
B	120	1	60	2	195	<1				
	170	1	60	2	220	<1				
	1,050	50	710	46	1,290	57				
	1,000	66	870	60	1,220	72	1,700	480		
C	400	20	290	12			1,750	400		
	600	30	350	21			2,150	450		
	940	105	680	70			3,400	560		
	380	24	150	20					730	36
	140	<1	50	<1					230	<1
A	45	1.2	45	1.2			All samples from same profile on fringe of soil anomaly			
	55	<1	55	<1						
B	450	<1	60	1.5	600	<1				
	130	<1	60	<1	195	<1				
C	70	<1	70	<1						
	90	<1	90	<1						

It is considered probable that the cold-extractable copper is related to the formation of metallo-organic compounds and that much of the copper in the A horizon as a whole is firmly fixed in the sesquioxides and within the lattice of low base exchange clay minerals.

In the B horizon the copper is markedly concentrated in the lateritic nodules as compared to the red-brown loamy matrix. The metal content of the latter is intermediate between that of the overlying A horizon and the underlying C horizon (Table 4). The preferential concentration of copper in the nodules indicates that in this horizon also, copper is closely associated with the sesquioxides. It seems likely that the copper was sorbed by, and coprecipitated with, the sesquioxides in the B horizon. The source of the sesquioxides is debatable; it is commonly held that they are in part

derived from the overlying A horizon but that they are mostly leached from the underlying rock and precipitated at or near the upper level of the seasonal water-table. This latter supposition is supported by the presence of a strongly bleached zone in the deeper parts of the C horizon.

The association of copper with sesquioxides is again evident in the C horizon. Within the zone of groundwater fluctuation, the C horizon is characterized by red mottling, the red areas being due to the presence of hydrated ferric oxides. Analyses show that there is up to five times as much copper in the red patches as compared to the content of the pallid matrix, wherein at least part of the iron is apparently in the ferrous state. The association of copper with manganese is also evident in the C horizon, as shown by the very high metal content of patches of manganiferous wad

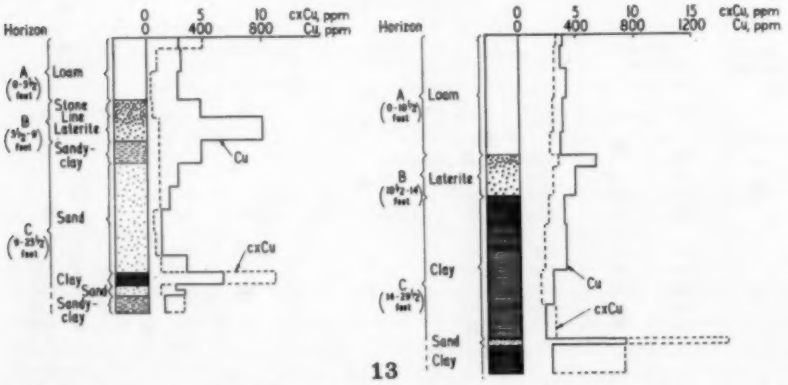

FIG. 12 (left). Distribution of anomalous copper in relation to soil horizon and clay bands in the soil profile, Baluba.

FIG. 13. Accumulation of anomalous copper in a permeable sandy layer of the C horizon, Baluba (cf. Fig. 12).

that are commonly present, particularly near mineralization (Table 4). Marked local changes in the lithology of the parent material can also affect metal distribution in the C horizon (Figs. 12, 13). Thus, concentration of copper in argillaceous bands within predominantly arenaceous profiles is considered to be due to their higher clay content. Although the clay minerals of this environment are unlikely to have a particularly high base exchange capacity, it appears possible that much of the copper in the argillaceous bands is loosely held in exchange positions in view of the marked rise in the cold-extractable copper content, which is proportionally several times greater than the increase in total copper. In places, an increase in copper content is associated with sandy strata within an argillaceous profile. Tentatively, this is attributed to the relative permeability of these bands as compared to the rest of the profile. Groundwaters from mineralization tend to be channelled through the more permeable zones wherein copper is preferentially deposited

despite the higher base exchange capacity of the relatively impermeable parts of the profile. Yardley (19) has observed a similar correlation between copper content and local variations in permeability within soils in North America.

Attention in the preceding paragraphs has been concentrated on the total copper content. The distribution of cold-extractable copper also shows a well-marked but different pattern of variation within the profile. In background areas, the maximum cold-extractable copper content occurs in the A_1 horizon where it is probably associated with the small amount of organic matter present, as previously mentioned. Near mineralization, the cold-extractable copper content generally rises again in depth on passing into the B horizon and the content in the C horizon may be many times greater than that of the corresponding A_1 horizon. However, where the ore-horizon has been extensively leached, e.g. as at Chibuluma, there may be no detectable cold-extractable copper anomaly even in the C horizon. Where a cold extractable copper anomaly is detected in the C horizon there is usually a marked increase in the proportion of cold-extractable : total copper, particularly in the vicinity of mineralization. This is particularly noticeable where there is an increase in clay content and in the presence of manganiferous wad. It is thought that the readily-soluble copper is associated with an increase in base-exchange capacity and with the presence of metal loosely absorbed on colloidal hydrous oxides.

Poorly-drained Profiles.—Typically, the poorly-drained dambo soils are composed of two major horizons, an organic-rich A_0 horizon and a pallid G horizon containing only minor amounts of organic matter. Although a part of the surface horizon of most dambo soils must be of transported origin, much of the profile, in some dambos at least, has been shown to be residual (10).

In general, the total and cold-extractable copper content is highest in the A horizon of the poorly-drained soils and there is a progressive decrease in metal content with depth. However, in the main seepage areas that commonly occur towards the center of the dambo, the copper content is higher in the underlying G horizon. A tendency to increase with depth was noted by Govett in dambo soils outside the main seepage area, but only in those parts of the dambo that lay nearest to mineralization on the adjoining interfluves.

Within the dambos, there is a marked tendency for copper to accumulate in the main areas of groundwater seepage. Govett (10) has shown that the exchange capacity of the organic matter of these soils is considerably higher than that of the clays, and there is little doubt that much of the copper, particularly the high proportion that is cold-extractable, is held as metallo-organic compounds. However, the relationship between organic matter and copper content is not a simple one, as shown by the fact that the decrease in organic content of the dambo soils with depth is much more rapid than is the decrease in copper content.

In addition to the important, even dominant, role of organic carbon, it is probable that the clay minerals also play an appreciable part in the fixation of copper.

Comparison of Anomalies Developed in Freely-drained and Poorly-drained Soils

Mineralizations of similar width and grade underlying freely-drained and poorly-drained soils at Baluba give rise to the total copper anomalies with peak values of 700 ppm and 4,500 ppm Cu respectively. An even more marked difference is observed in the corresponding cold extractable copper anomalies which rise to maxima of 20 ppm cxCu and of 1,100 ppm cxCu.

The effects of erosion on anomaly patterns is most marked in freely-drained soils where exposure of the B or C horizons results in a considerable increase in the magnitude of surface copper anomalies. By contrast, removal of the organic rich A horizon of the dambo soils and exposure of the G horizon will cause little change in the surface copper content.

Reference has already been made to evidence of the residual nature of the poorly drained soils of the headwater dambos in the Copperbelt and also to the dynamic character of these dambos that develop at the expense of the freely drained interfluves.

As a result, residual anomalies in dambo soil reflect

(a) the metal distribution pattern in the parent material which, according to the depth of erosion, may be either the A, B or C horizon of the original freely drained profile;
(b) the extent to which pre-oxidation had left residual copper in a form that could be mobilized even under the anaerobic, reducing conditions characteristic of the dambo environment, on the one hand; and on the other hand,
(c) the extent to which copper had been removed by leaching prior to the onset of dambo conditions.

In addition to metal derived from oxidized ore underlying the dambos, copper and cobalt will also be precipitated in the dambo seepage areas from groundwater solutions draining from the freely drained sections of the deposits that extend beyond the dambo margins (17). In headwater dambos the seepage area normally lies towards the center of the dambo. Further downdrainage the main seepages are found in depressions and at the break of slope marking the boundary between the two major soil types. Whatever their situation, the transported metal will give rise to an anomaly in the soils around the seeps. Seepage anomalies of this type may, of course, be superimposed on any residual anomaly derived from ore minerals lying beneath the dambo.

In residual anomalies, the bulk of the metal occurs firmly bonded by clay minerals and the sesquioxides and is not readily extractable. On the other hand, much of the metal deposited from groundwaters in seepage areas tends to be loosely held by organic matter and freshly precipitated ferric hydroxide. Consequently, whereas the proportion of cold-extractable copper in freely drained near-surface soil rarely exceeds 1 to 5 per cent of the total copper content, the ratio in dambo seeps is generally greater than 25 per cent. Where ore occurs beneath a dambo, the anomaly in the overlying soil is com-

posed of both residual and superimposed metal. In the one example of a composite anomaly the proportion of cold-extractable Cu ranged from 10 to 25 per cent.

Influence of Lithology on Anomalies.—In addition to the effect of rock type on the background copper content in the soil, there are also considerable variations in the anomalies developed over lithologically different host rocks. Thus, the near-surface soil anomaly over the argillaceous ore horizon at Baluba is more than twice as intense as that related to the arenaceous ore horizon at Chibuluma, despite the fact that the latter deposit is higher grade. A similar, though less marked, decrease in the magnitude of the anomaly over the more arenaceous sections of the Baluba deposit is also related to the change in lithology along the strike (e.g. cf. Figs. 5a and 5c).

This effect is apparent in all soil horizons but is most marked in the A horizon. Furthermore, over arenaceous host rocks there is no sharp peak in the A horizon anomaly (cf. Figs. 10 and 11). The reasons for these differences are believed to be (a) more intense leaching of the more permeable arenaceous host rocks and (b) the higher content of clays and sesquioxides in the shales which would favor the retention of residual copper.

In addition to the nature of the host rock; the lithology of the wallrocks may also influence the anomaly. Thus, at Musenga, the low copper contents in soils overlying the mineralization and the higher values over the downslope shales are attributed to the leaching of metal from the deposit and its re-deposition by exchange reactions with the clay minerals, sorption on the sesquioxides, or by precipitation due to a higher pH, in the dolomites, dolomitic shales and shales (Fig. 8).

Grade of Ore

Although soil anomalies are markedly influenced by the local environment and the intensity of past oxidation and leaching, the magnitude of the anomalous values in freely-drained profiles tends to reflect the grade and width of the underlying mineralization provided the bedrock lithology and relief remain essentially constant. Thus, at Baluba, with decrease in the grade and width of ore from over 30 feet of more than 3 per cent copper underlying Traverse 5b, to 5 feet of less than 2 per cent copper on Traverse 6a, there is a gradual decrease in the anomaly peaks in the near surface soils from 700 ppm to less than 150 ppm. Anomaly peaks of 250 and 180 ppm Cu occur on neighboring traverses that cross intermediate grades of ore. A similar relationship between anomaly peak values and ore grade was observed at Musenga.

Ore grade and width may also affect the shape of anomalies. At Baluba, the A horizon anomalies have distinct, sharp peaks over the ore body along Traverse 5a and 5b in contrast to the flatter anomalies observed over subeconomic mineralization on Traverses 6a and 6b. The foregoing refers only to argillaceous ore horizons; no marked anomaly peaks were observed in the A horizon over ore in arenaceous hostrocks.

Mode of Dispersion

Evidence that the major agent of dispersion of metal from the ore bodies is the groundwater has been presented in discussing the effect of the topography on the form of the anomalies. Copper moving in solution tends to be fixed by sorption and coprecipitation with sesquioxides in the freely-drained soils and by adsorption on organic matter in the seepage areas of the dambos. In addition, some copper will be fixed by exchange reactions with the clays.

In fact, most of the copper in the B horizon of freely-drained soils is considered to have been co-precipitated with the sesquioxides. At the present day, only the lower parts of the B horizon are normally within the zone of groundwater fluctuation.

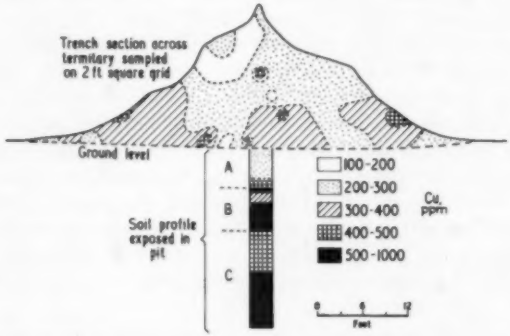

FIG. 14. Distribution of copper in a termitary and underlying soil in the vicinity of mineralization, Baluba.

Even in exceptionally wet seasons, most of the A horizon of the freely-drained soils remains above the water table and the saline dispersion of copper in the present-day groundwater cannot directly account for the anomaly in the A horizon. Furthermore, the suggestion that the A horizon anomaly is a palimpsest anomaly emplaced by metal-bearing groundwater solutions at some time in the past, is considered improbable. Quite apart from pedological considerations, a near-surface palimpsest anomaly would imply that past groundwater movements were identical to those of the present day, as the anomalies in all three soil horizons have similar upslope and downslope extent.

As previously mentioned, the evidence is against any substantial mechanical dispersion of the copper by soil creep or sheet wash. Furthermore, mechanical movement of soil cannot explain the upslope extension of anomalies in all three horizons.

The possibility that termites have raised much material from the C horizon is not supported by the observed distribution of copper in the termitaries. Figure 14 strongly suggests that the vast majority of the material of the termitary is derived from the A horizon.

The presence of significantly higher cold-extractable copper contents in the organic topsoil of freely-drained profiles compared to the A horizon as a whole suggests that metal may be taken up by the vegetation and returned to the surface by the decay of organic litter (Figs. 5a, 10). Some of this copper may be leached and tend to be fixed in the soil through which the percolating solutions pass. If this is true then the suggestion that deep-rooted vegetation may play a dominant part in the development of A horizon anomalies could also satisfactorily explain the coincidence of the anomalies in all three horizons of the soil. However, no unequivocal copper anomaly was detected in the vegetation over mineralization but this could be due to the very limited number of samples collected and the fact that only the twigs were examined.[2]

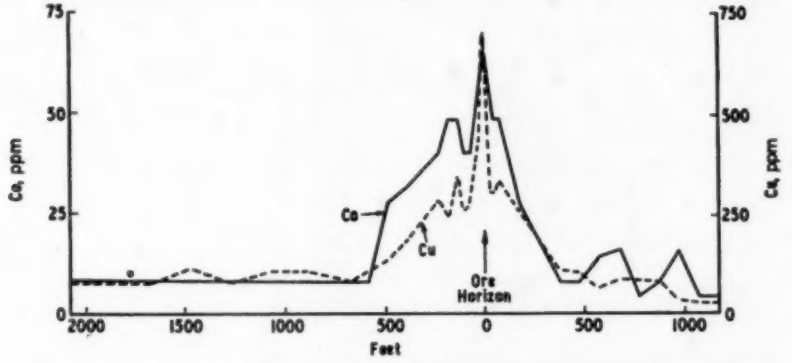

FIG. 15. Comparison of copper and cobalt anomalies in near-surface soil, Traverse 5a, Baluba.

Distribution of Cobalt

A selection of samples from Baluba were analyzed for total cobalt, the results being presented in Figures 7, 9 and 15.

Anomalous cobalt values have a similar lateral distribution to those of copper, both in the near-surface freely-drained soils of the interfluve areas and in the poorly-drained dambo soils. The average ratio of copper to cobalt in the near-surface freely-drained soil anomaly on Traverse 5c is approximately 20:1 as compared to an average of 10:1 on Traverse 5a. These ratios reflect fairly closely the relative contents of copper and cobalt in the primary ore as revealed in drill holes. Furthermore, a ratio of 20:1 was also observed in the poorly-drained soils of the dambo downdrainage from the mineralized horizon underlying Traverse 5c. However, in the poorly-drained soils overlying mineralization on Traverse 9 the ratio of copper to cobalt is markedly different from that suggested by borehole data; a ratio

[2] Recent work by J. R. Jay (13) has demonstrated the existence of anomalous amounts of cobalt in the vegetation growing over the Baluba copper-cobalt deposit. His samples were not analyzed for copper.

of 20:1 in the dambo as compared to 10:1 in the ore. It is not known whether this apparent lack of agreement is due to a local variation in the primary metal ratio in depth or whether it is a result of differences in the mobilities of the two elements in a poorly-drained weathering environment.

Despite the general similarity of the distribution pattern of these two metals in near-surface soil, the factors affecting the dispersion of cobalt do not appear to be identical with those for copper. In particular, from the very limited number of freely-drained profiles studied, cobalt shows no tendency to accumulate with the sesquioxides of the B (laterite) horizon as does copper (Fig. 16). Near mineralization the cobalt content shows a general increase with depth irrespective of the soil horizon whereas in soils with only background cobalt contents there is little variation throughout the soil profile. It is therefore probable that cobalt is not adsorbed on or co-

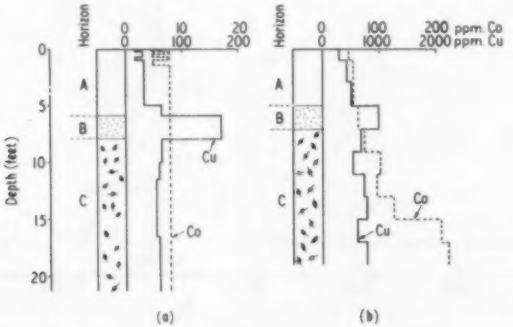

FIG. 16. Distribution of copper and cobalt in freely drained profiles, Baluba. Fig. 16(a) is 2,000 ft. and Fig. 16(b) is 100 ft. downslope from ore horizon (gradient < 1 degree).

precipitated with hydrous iron oxides. In areas of groundwater seepage, on the other hand, there is a marked accumulation of cobalt, as well as copper, in the organic-rich soil. Further work is in progress aimed at investigating the factors controlling the dispersion of cobalt under the prevailing range of conditions, with particular reference to the effect of manganese oxides and organic matter.

Influence of Contamination on the Results

Apart from obvious dumps and roads, which were avoided, the only possible sources of contamination in the study areas are smelter slag and fumes. In one area at Mufulira West, smelter slag has been widely distributed on the surface, probably as a top dressing, on agricultural plots. In order to determine the extent of this contamination a soil traverse was sampled at two depths, 0 to 3 and 12 to 15 inches. The results, presented in Fig. 17, show a very erratic distribution of copper at 0 to 3 inches, which is no doubt related to contamination. At a depth of 15 inches, however, a

broad smooth anomaly is detected over the ore-horizons. This anomaly, which is typical of those found in freely-drained soils over other arenaceous host rocks, rises to a maximum value of only 150 ppm Cu and shows no distinct peak over the ore horizons.

Restriction of slag contamination to the upper topsoil is attributed to the fixation of copper by soil organic matter as metal is released by the slowly decomposing slag. It is of course probable that some of this copper will, in

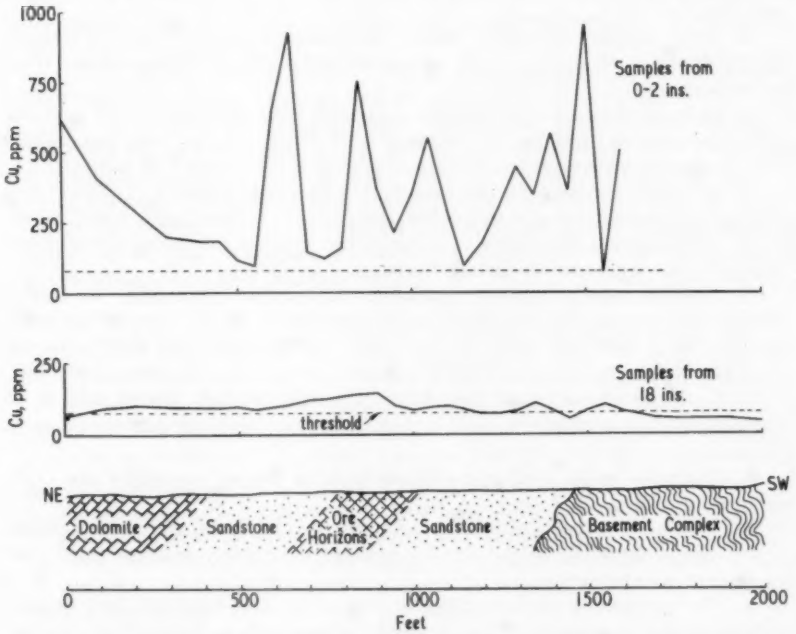

FIG. 17. Illustrating erratic metal values in the topsoil due to contamination from smelter slag; the anomaly at 18 inches depth is related to the underlying ore horizon, Mufulira.

time, be transported to greater depths and be re-precipitated. However, no such secondary accumulations have been observed and the period of time required before they become significant is unknown.

The results obtained from background soil samples collected 5 miles downwind from the smelter at the Roan Antelope Copper Mine (Fig. 1) indicated that the contaminating effect of smelter fumes probably does not exceed 25 ppm Cu in the top 12 inches of the soil.

These observations indicate that the anomalies described on previous pages can be taken as truly representing the natural pattern of metal distribution. It is, of course, possible that contamination could be an important factor in prospecting more seriously affected areas (6).

CONCLUSIONS

Although the results of these studies were obtained in only a limited number of areas, the conclusions summarized below are considered to be generally applicable in the Northern Rhodesian Copperbelt and similar areas elsewhere.

1. Geochemical anomalies were observed throughout the profile of both poorly-drained and freely-drained residual soils derived from mineralized bedrock.

2. Total copper anomalies related to mineralization have considerable lateral extent and are normally asymmetrically extended downslope from the suboutcrop.

3. In freely-drained soils both the magnitude and sharpness of the anomaly peaks immediately over the ore increase with depth. Away from mineralization maximum values are commonly obtained in the lateritic B horizon.

4. In poorly-drained dambo soils both in seepage areas and where they overlie suboutcropping mineralization the copper content again tends to increase with depth. Elsewhere in dambos, the greatest concentration of metal occurs in the organic-rich surface horizons.

5. Cold-extractable copper anomalies are readily detectable in freely-drained soil over argillaceous host-rocks, particularly in the deeper soil horizon, and in all horizons of the dambo soils. Over arenaceous host rocks, on the other hand, the cold-extractable copper content may be consistently low.

6. Cold-extractable anomalies have a much smaller lateral extent in freely-drained soils than the total copper anomalies, and are commonly more erratic.

7. In dambo soils, total and cold-extractable copper anomalies are comparable in width.

8. Anomalies developed in the swampy dambo soils are several times greater than those developed in the near-surface freely-drained soils over equivalent mineralization.

9. The magnitude of anomalies is related to the lithology and permeability of the host-rock. The strength of anomalies, particularly in the A horizon of freely-drained soils, is usually much less over ore in arenaceous compared to that over equivalent mineralization in argillaceous host-rock. Even where leaching has been exceptionally intensive, anomalies are readily detectable in the B horizon.

10. The source of secondary anomalies is the leached suboutcrop of the deeply oxidized ore bodies, and the grade of the leached suboutcrop may be markedly lower than that of the original ore body.

11. Under relatively constant conditions of geology, pedology, and topography, variations in the magnitude of anomalies in the freely-drained soils may reflect the width and/or grade of mineralization in the bedrock.

12. Dispersion of copper from mineralization is dominantly saline, via the agency of the groundwater.

13. Upslope extensions of anomalies in freely-drained soils are attributed to local groundwater movements contrary to the surface topography.

14. The effects of soil creep and termite activity on the dispersion of metals from mineralization are very limited.

15. Copper anomalies in the A horizon of the freely-drained soils are considered to be probably due to the transportation of copper from the C horizon to the surface by deep-rooted vegetation.

16. Important factors controlling the development of anomalies in the freely-drained soils include (a) precipitation of copper with the sesquioxides and (b) fixation of the metal in exchange positions on clays, manganese wad and organic matter. The relative importance of these factors is determined by the particular soil horizons.

17. In poorly-drained dambo soils copper is largely fixed in exchange positions on the organic matter and to a lesser extent on the clays.

18. The cxCu : Cu ratio is considerably higher in poorly-drained dambo soils than in freely-drained soils. In poorly-drained soils over mineralized bedrock the cxCu : Cu ratio is lower than in seepage anomalies where the metal has been precipitated from groundwater solutions.

19. In general terms, the distribution of cobalt tends to follow that of copper, although cobalt does not show the same tendency to accumulate in the B horizon of freely-drained profiles.

GENERAL CONCLUSION CONCERNING THE PRACTICAL APPLICATION OF THE METHOD

Since these studies were initiated, geochemical soil surveys have become an established prospecting technique for copper, not only on the Copperbelt but also in other parts of Africa, with the exception of the deserts. Under average sub-tropical and tropical conditions, the method has proved to be a reliable guide in locating mineralized bedrock in areas of residual soil cover. However, despite the widespread application of geochemical soil surveys, the most efficient and reliable field and analytical methods to be employed in any specific area can only be established by an appropriate orientation survey.

With experienced supervision, all routine sampling and analytical procedures can be carried out by unqualified personnel assisted by local labor. The principal difficulties arise not in the detection of anomalies but in distinguishing those anomalies that merit exploration in depth, usually by costly drilling operations. Material assistance in interpretation can be gained by first testing likely anomalies by close pitting and profile sampling to bedrock. The importance of determining the trend of metal distribution in the lower soil horizons, the nature of the bedrock and the cxCu : Cu ratio—points already emphasized in preceding papers—cannot be overstated. Geochemical data must, of course, always be interpreted in terms consistent with the local geology and hydrological conditions. In many parts of Africa the bedrock is very poorly exposed and in these circumstances the interpretation of anomalies is semi-empirical at best and dependent largely on experience. The investigation of additional geochemical criteria could well advance prospecting technique in these areas, particularly if the research was carried out

in conjunction with an investigation of appropriate geophysical, geobotanical, and other methods.

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LONDON,
Nov. 17, 1960

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MINOR ELEMENTS IN A METASOMATIC ZONE RELATED TO A COPPER-BEARING PYRITE DEPOSIT

YOSHIMASU KURODA

ABSTRACT

The behavior of minor elements in the wall rocks of a copper-bearing pyrite deposit (Hitachi Mine, Japan) is considered. The wall rocks of the deposit are anthophyllite-cordierite rock, etc. The metasomatism and mineralization are very similar to that of the Orijärvi region in Finland. As the ore minerals increase, the metasomatic minerals such as anthophyllite and/or cordierite increase. In the metasomatic zone Mg and Fe increase and Ca decreases. In regard to the behavior of minor elements, Sr is conformable to Ca. Ni, Cr, and Co show no relation to the increase of Mg and Fe. The behavior of minor elements is similar to that in the wall rocks of epithermal deposits (Kuroko = Black Ores, etc.). In general, minor elements were easily removed with the removal of the corresponding major elements but their concentration was only slightly increased with an increase of the corresponding major elements.

INTRODUCTION

MINOR elements in various materials, such as ore minerals, have been well investigated, but their behavior during ore formation has been scarcely examined. The variation of major elements in wall rocks has been studied but it is necessary to determine also the significance of minor elements in the study of ore genesis. In the course of magmatic differentiation, the behavior of minor elements has been looked into and it is useful in the study of igneous rocks. Unfortunately, in metamorphic or metasomatic rocks, the technique of separation of the minerals is difficult. Minor elements in wall rocks of ore deposits, therefore, have received very little study. Recently, analyses of minor elements in ore minerals such as in pyrite have been made in Japan. According to the results, there are remarkable differences due to the differences in types of ore deposits. In addition, certain results pertaining to the behavior of minor elements in wall rock alteration of epithermal ore deposits in Japan have been obtained.

This paper reports on a study of minor elements in the wall rocks of the Hitachi Mine, northeastern Japan.

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DESCRIPTION OF THE OUTCROPS UNDER CONSIDERATION

As the general geology of the Hitachi district has already been described by myself (5, 6) and other geologists, it is reviewed only briefly here.

The Hitachi Mine is one of the largest copper-bearing deposits in Japan and the wall rocks are various metasomatic rocks such as anthophyllite-cordierite rock, which are very similar to those of the Orijärvi region.

It is located in metamorphic rocks of amphibolite facies (zone III) derived from the Paleozoic formation (probably Visean), which is intruded by the Irishiken granodiorite (probably Late Paleozoic or Early Triass) at the northern part. As a forerunner of the granodiorite, the Kaminesan gabbro is exposed in the northeastern part of the orefield along the southern side of the granodiorite (Fig. 1). The gabbro is sheared and is metamorphosed

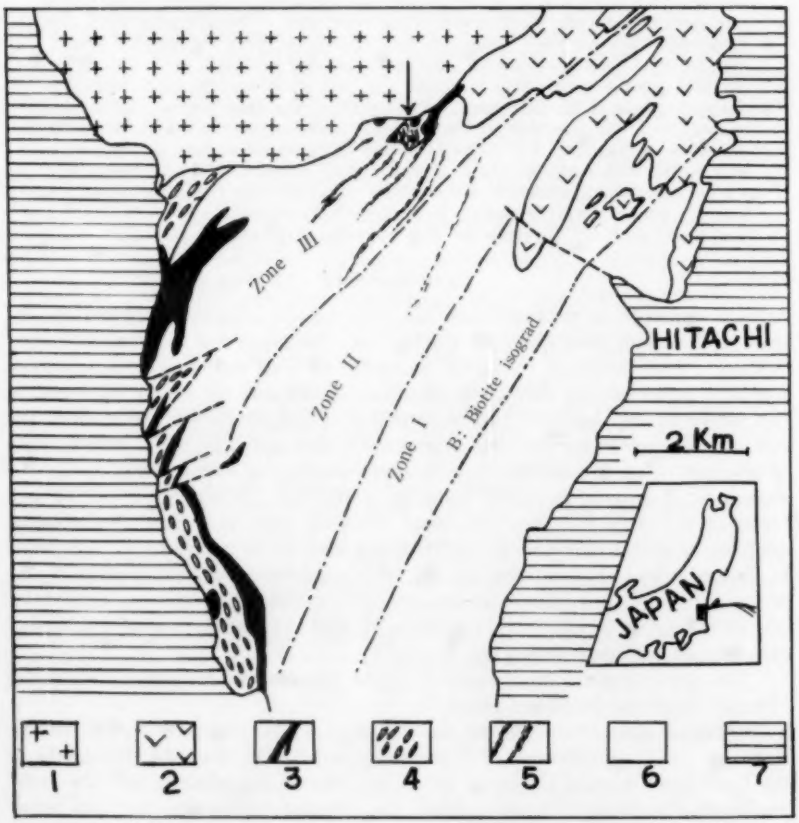

FIG. 1. Geological map of the Hitachi district. 1: Irishiken granodiorite. 2: Sheared granite. 3: Ultrabasic and basic rocks. 4: Western Hitachi gneisses. 5: Ore-bearing metasomatic rocks. 6: Hitachi Paleozoic formation. 7: Tertiary and Quaternary formation. Arrow shows the Kaminesan gabbro area under present study. Zones I, II and III nearly correspond to greenschist facies, epidote-amphibolite facies, and amphibolite facies respectively.

TABLE 1

CHEMICAL COMPOSITIONS OF A-TYPE SERIES

(Parts per million $\times 10^3$)

	1	2	3	4
Si	230	245	286	214
Ti	7	12	4	3
Al	97	75	58	68
Fe‴	20	41	24	13
Fe″	10	18	15	50
Mg	30	42	55	110
Ca	78	52	6	9
Na	2	1	1	3
K	4	4	2	3
FeS_2	0.8	8.8	38.1	46.3
$CuFeS_2$	0.6	—	0.6	2.6
Fe in ores	0.6	3.9	17.9	22.4

1: Hornblende-gabbro. 2: Biotite-anthophyllite-quartz-dioritic rock (partly metamorphic texture). 3: Anthophyllite-cordierite rock (metamorphic texture). 4: Ore-bearing anthophyllite-cordierite rock.

along the shear planes to various metasomatic rocks, e.g., anthophyllite-cordierite rock (type A), biotite-cordierite rock (type B), sillimanite-potash feldspar-quartz rock (type C), and garnet-epidote-diopside amphibolite (type D), among which the first three types are closely connected with the ore deposits; that is, the more abundant are the metasomatic minerals such as anthophyllite and cordierite, the more abundant are the ore minerals.

The Paleozoic formation is also partly altered to metasomatic rocks similar to those mentioned above, however, of rather lower grade than the above, but still containing ore deposits. The ore deposits, therefore, formed during the metasomatism, which may have happened during high-temperature, pneumatolytic conditions (6).

TABLE 2

CHEMICAL COMPOSITIONS OF B-TYPE SERIES

(Parts per million $\times 10^3$)

	5	6	7	8
Si	279	280	264	160
Ti	3	3	4	6
Al	62	65	48	98
Fe‴	13	14	20	44
Fe″	37	17	25	28
Mg	20	25	48	52
Ca	46	14	7	11
Na	9	3	2	2
K	5	2	1	2
FeS_2	—	67.4	74.9	121.5
$CuFeS_2$	—	1.7	0.9	4.6
Fe in ores	—	31.9	34.7	60.5

5: Biotite-hornblende quartz-diorite. 6: Biotite rock (partly quartz-dioritic texture). 7: Cordierite-biotite rock (metamorphic texture). 8: Ore-bearing cordierite-biotite rock.

TABLE 3

MINOR ELEMENTS IN A-TYPE SERIES

(Parts per million)

	1	2	3	4
As	—	—	—	—
Sb	100	—	250	—
Ge	—	—	—	—
Ga	18	25	28	18
Sn	—	—	—	—
Ni	50	10	35	25
Co	20	12	22	20
Cr	40	—	25	25
V	200	230	180	60
Cu	80	280	250	800
Pb	12	40	30	40
Zn	—	250	400	2,000
Mn	800	1,200	1,500	1,300
Sr	750	400	40	80
Ba	350	350	700	1,000
Ni × 1,000/Mg	1.7	0.2	0.6	0.2
Ni × 1,000/total Fe	1.7	0.2	0.6	0.3
(Ni + Cr + Co) × 1,000/Mg + total Fe	1.8	0.2	0.7	0.3
V × 1,000/total Fe	6.6	3.7	3.1	0.7
Sr × 1,000/Ca	9.5	7.7	7.7	8.3

Numbers are same as those in Table 1.

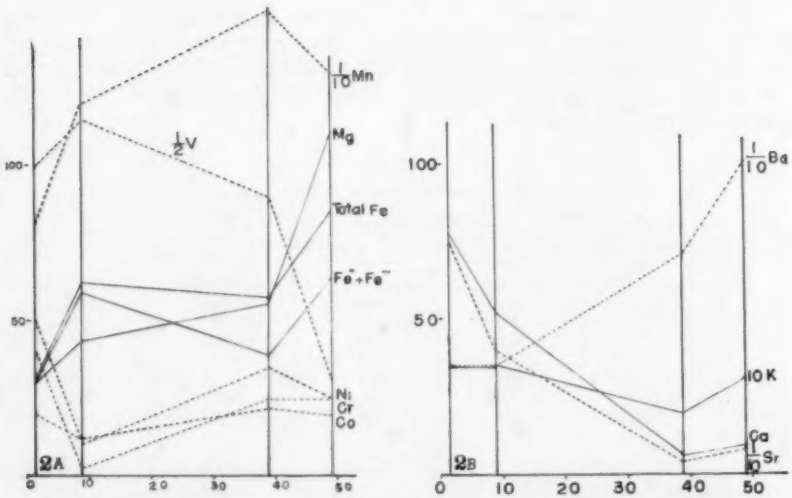

FIG. 2. Variation diagram of minor and major elements in relation to the amount of pyrite and chalcopyrite for A-type. Figures are parts per million but minor elements and parts per million × 1,000. Total Fe means all Fe in silicates and ores. Fe″ + Fe‴ means all Fe except that in pyrite and chalcopyrite.

I believe there have been two series of metasomatism; one formed the A-type metasomatic rocks derived from the hornblende-gabbro (a member of the Kaminesan gabbro) and the other formed the B-type metasomatic rocks derived from the quartz-diorite (a member of the Kaminesan gabbro). The former is from the Sasame O m Gallery of the mine and its occurrence is described in a previous paper (5). Over a width of several meters, the gradual transitional change from the hornblende-gabbro (No. 1 in Table 1) to the ore-bearing anthophyllite-cordierite rock (No. 4), through the intermediate stage such as anthophyllite rock (No. 3), can be clearly traced in the field and by the microscope. The chemical changes are shown in Table 1.

The latter is from the Sasame Ue 65 m Gallery and its occurrence is also described in my previous paper (5). There also can be clearly traced, within a width of several meters, the transition from the quartz-diorite (No. 5 in Table 2) to the ore-bearing biotite-cordierite rock (No. 8), through the intermediate stage of the biotite rocks (Nos. 6, 7). These chemical changes are shown in Table 2.

RELATIONS BETWEEN MINOR ELEMENTS AND MAJOR ELEMENTS

A-Type Series.—Minor element compositions of the A-type rocks listed in Table 1 are shown in Table 3. It is evident from the table that during metasomatism Cu, Pb, Zn, Mn, and Ba increased in abundance whereas Sr and V decreased. Ni, Co, Cr and Ga scarcely varied (Figs. 2A, B).

It is natural, of course, that Cu, Pb and Zn increase, because ore minerals such as pyrite, chalcopyrite, zincblende, and galena increase in the process. Among the major elements the increase of Mg and Fe and the decrease of Ca are remarkable. According to Wager and Mitchell (9) Sr seems to enter plagioclase, replacing Ca. In this case the amount of plagioclase varies from 68.5 percent (in the hornblende gabbro: No. 1) to 4.2 percent (in the ore bearing anthophyllite-cordierite rock: No. 4) and the An content also varies from An 90–50 to An 10–5. The ratio of Sr × 1,000/Ca is almost constant (7.7–9.5), indicating a similar behavior of both elements. Thus it is natural that Sr decreases (from 750 ppm to 80 ppm) with the decrease of Ca.

It is said that Ni and Cr are enriched in the mafic minerals, such as olivine, of the early magmatic stage of igneous rocks, with enrichment of Mg (9), and they are chemically similar to Fe. Therefore, it may be considered that Ni and Cr may be enriched with the enrichment of Mg and Fe. They, however, decrease and the ratio of Ni × 1,000/Mg and Ni × 1,000/Fe also decreases. Since the mafic mineral in the hornblende-gabbro (No. 1) is only hornblende, these elements may be present mainly in hornblende. In the change from the hornblende-gabbro (No. 1) to the anthophyllite-bearing quartz-dioritic rock (No. 2), hornblende (28% in volume in No. 1 rock) varies to anthophyllite (15% in volume in No. 2 rock) and ore minerals do not increase. These elements should decrease in the quartz-dioritic rock (No. 2). Whereas in the anthophyllite-cordierite rocks (Nos. 3, 4), in which the amphibole is anthophyllite (11.5% and 14.6% in volume respectively),

these elements are rather more abundant than in the quartz-dioritic rock (No. 2). Thus it may be considered that small amounts of Ni, Co and Cr enter ore minerals, although very small amounts.

Vanadium decreases in the metasomatic rocks, although it seems to increase in the ore-bearing rock. The ratio of V × 1,000/Fe also decreases from 6.6 to 0.7.

Ba seems to replace K in minerals such as potash feldspar. As in the A-type rocks, potash feldspar is not found, it seems to enter plagioclase and/or biotite or to be present as barite of separate phase.

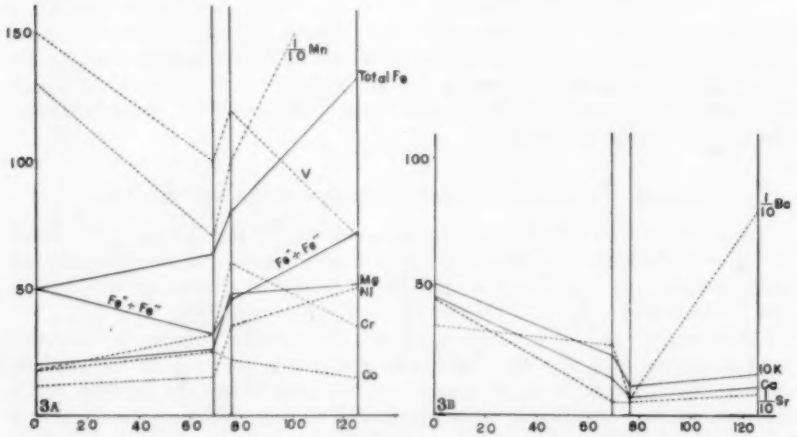

FIG. 3. Variation diagram of minor and major elements in relation to the amount of pyrite and chalcopyrite for B-type. Figures same as Figure 2.

B-Type Series.—The results of the analysis of the minor elements of the B-type are shown in Table 4. The increased elements are Ni, Cr, Cu and Zn and the decreased elements are Sr and V. Ga, Co and Pb are scarcely variable. Ba does not show any consistent variation (Figs. 3A, B).

In regard to the major elements, Ca decreases and Mg and Fe increase. Sr also conforms to the decrease of Ca, though it is not as distinct as for the case of A-type; that is, the ratio of Sr × 1,000/Ca is 3.6–9.7. However, it is related to the decrease of plagioclase and its An content [No. 5: 47.5 in volume (An 65–30), No. 6: 31.4 (An 30–10), No. 7: 27.6 (An 30–10), No. 8: 12.4 (An 10–5)].

Ni and Cr increase slightly with the progress of metasomatism. Although the values of the ratios of Ni × 1,000/Fe, Ni × 1,000/Mg and (Ni + Cr + Co)1,000/Mg + Fe are as low as in the intermediate or acidic igneous rocks, they are almost constant, as shown in Table 4. Therefore, it may be considered that they increase with the increase of Fe and Mg, but their absolute values are rather low compared with their values in rocks

having as high Mg-Fe contents as the biotite-cordierite rock (No. 8). The mafic minerals in the quartz-diorite (No. 5) are biotite (13.5%) and hornblende (16.0%) and in Nos. 6, 7 and 8 rocks, hornblende is absent whereas the biotite content is 31.5, 30.1 and 17.6% respectively. Thus they may enter into ore minerals such as pyrite and chalcopyrite, although in slight amounts.

TABLE 4

MINOR ELEMENTS IN B-TYPE SERIES

(Parts per million)

	1	2	3	4
As	—	—	—	—
Sb	—	—	—	—
Ge	—	—	—	—
Ga	20	15	18	22
Sn	—	—	—	—
Ni	12	15	35	50
Co	18	25	22	15
Cr	18	32	60	35
V	150	100	120	70
Cu	40	500	400	2,500
Pb	10	25	18	18
Zn	—	—	200	500
Mn	1,300	700	1,000	2,000
Sr	450	50	50	80
Ba	350	270	60	800
Ni × 1,000/Mg	0.6	0.6	1.4	1.0
Ni × 1,000/total Fe	0.6	0.2	0.4	0.4
(Ni + Cr + Co) × 1,000/Mg + total Fe	1.0	0.8	0.9	0.6
V × 1,000/total Fe	3.6	1.6	1.4	0.5
Sr × 1,000/Ca	9.7	3.6	7.0	7.1

Numbers are same as those in Table 2.

Vanadium decreases in spite of the increase of Fe and ore minerals. The ratio of V × 1,000/Fe also decreases from 3.6 to 0.5.

The general tendencies of the behavior of minor elements are very similar to the case of A-type.

CONSIDERATION

It is interesting that Cr, Ni, and Co do not increase during the metasomatism bringing about Mg-Fe enrichment. Of course, in the case of B-type, Ni and Cr increase slightly, and even in A-type, Ni, Cr, and Co increase from No. 2 rock to No. 4 rock, though they decrease from No. 1 rock to No. 2 rock. However, the degree of the increase of these minor elements is larger in B-type rather than in A-type. It may be due to the fact that in the case of B-type, Fe increases more than in the case of A-type; that is, in A-type, Fe increases from 30 (No. 1) only to 86 (No. 4), though Mg increases from 30 to 111; but in B-type Fe increases from 50 (No. 5) to 182 (No. 8), though Mg increases from 20 to 52. (The Fe includes both Fe″ +

Fe‴ and Fe in ores.) In either case the abundance of Ni, Cr, and Co is rather low compared to the abundance of Mg and Fe in metasomatic rocks.

In the case of wall-rock alteration of certain epithermal ore deposits in Japan, Ni and Cr also increase slightly towards ore bodies (maximum 50 ppm) (1 and 2). Unfortunately, there is no analysis of rock in these papers (1 and 2). Of course, Mg and Fe probably increase considerably as in the case of the Hitachi Mine.

Sr also decreases in the altered wall rocks of epithermal ore deposits (1, 2, and 3), and it is conformable to the decrease of Ca.

In the granitization process of basic rocks Ni, Cr, and Co decrease towards the center of granitization, and this is conformable to the decrease of Mg and Fe (7). Cu also decreases in the granitization process of metadiabases or pelitic rocks (4).

Thus, it may be considered that minor elements readily decrease with a decrease of conformable major elements, but they do not increase so readily with an increase of conformable major elements.

However, V is quite variable in all cases, though it is said that it is similar to Cr in magmatic differentiation; that is, in one case it decreases and in other case it increases.

Ba increases in all cases, and it may be characteristic in hydrothermal and pneumatolytic metasomatism.

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Dec. 12, 1960

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A COMPARISON OF ANALYTICAL METHODS USED IN GEOCHEMICAL PROSPECTING FOR COPPER [1]

L. C. HUFF, T. G. LOVERING, H. W. LAKIN, AND A. T. MYERS

CONTENTS

PAGE
Abstract 855
Introduction 855
Description of samples 857
Geochemical prospecting tests 859
Citrate soluble heavy metal 859
Heavy metal 860
Chromographic copper 860
Dithizone copper 860
Biquinoline copper 860
Spectrographic analysis 861
Statistical distribution of copper 861
Comparison of analytical methods 864
Discussion of results 869
References 871

ABSTRACT

Analytical methods used in geochemical prospecting for copper were compared by analysis of samples of residual soil collected in duplicate near a copper-bearing vein at the Malachite mine, Jefferson County, Colo. In this area barren or "background" samples have a mean copper content of 58 ppm (parts per million) and anomalous samples containing copper derived from the vein have a mean copper content of 216 ppm. Most anomalous samples are above 100 ppm and most barren samples are below.

Geochemical prospecting tests, such as the spectrographic, biquinoline, dithizone and chromograph tests for copper and the citrate soluble and acid-soluble tests for total heavy metal, are almost as sensitive but are less precise and less accurate than standard quantitative trace analysis. Statistical techniques based chiefly upon the coefficient of variation show that the geochemical prospecting tests differ considerably among themselves in sensitivity, precision, and accuracy. This study indicates that the dithizone and the biquinoline tests for copper are the best for geochemical prospecting in this area.

INTRODUCTION

As more and more geochemical prospecting tests become available there is increasing need to compare and evaluate them. Geochemical prospecting tests are much simplified versions of standard analytical procedures and because of the simplifications are subject to much analytical error. Moreover

[1] Publication authorized by the Director, U. S. Geological Survey.

they are used under a wide variety of geologic situations and commonly are subject to large sampling errors. Because of the relatively large errors and the many numbers of samples involved it is appropriate that the comparison and evaluation of these tests be made by statistical methods.

Most statistical studies of geochemical data made previously concern either the error involved in sampling or the error involved in analysis. Sampling errors have been investigated for the determination of pH in soils by Youden and Mehlich (18) and the nitrogen, phosphorous, and potassium content of soils by Barker and Steyn (3). Analytical errors have been investigated for the ore metal content of soil by Craven (7) and McCarthy (12). Analysis of samples collected in duplicate has been used to indicate the total error of sampling and analysis by Gilbert (8) and by Hawkes and Bloom (9). Statistical methods have also been used to evaluate the significance of analytical differences by Shaw and Bankier (14) and by Tennant and White (17). In this study we wish to show how statistical methods can be used to select the best of several geochemical prospecting tests for a particular area.

Both the variation of ore metal content of the samples and the ability of analytical methods to detect the variation must be considered in geochemical prospecting. In particular, we would like to answer questions like the following: 1) What is the frequency distribution of ore metal among background samples? 2) What is the distribution of ore metal among the anomalous samples? 3) How do the analytical methods compare with respect to precision (ability to reproduce results)? 4) How do they compare with respect to accuracy (absence of bias)? 5) How do they compare in ability to distinguish anomalous samples that may be of significance in prospecting? And finally, 6) What is the least expensive method that is adequate to define the existing geochemical anomalies?

We have tried to answer these questions for residual soil from near a small vein-type copper deposit. Geological and geochemical-prospecting investigations made of this deposit have been described elsewhere by Huff (11) and only a brief description of the samples is required here.

The analytical methods used on these samples include six geochemical prospecting tests and, for comparative purposes, two quantitative laboratory methods. The geochemical prospecting tests include one suitable for use at the sample site, five suitable for use at a camp site or in a makeshift field laboratory, and one requiring spectrographic equipment ordinarily found only in well-equipped laboratories. The analyses were made by N. M. Conklin, H. E. Crowe, D. B. Hawkins, A. P. Marranzino, and C. E. Thompson.

The statistical comparison is based largely upon the use of the mean, the standard deviation, and the coefficient of variation (standard deviation divided by the mean) and each method is evaluated in terms of sensitivity, precision, and accuracy. Sensitivity is indicated in part by what is called here the discrimination—the number of categories in which concentrations can be expressed. Precision is taken as a measure of reproducibility and accuracy as a measure of agreement with quantitative laboratory methods. Similar comparisons for other areas might lead to entirely different evalua-

tions of the analytical methods but similar statistical treatment may be widely applicable.

This investigation is a byproduct of other U. S. Geological Survey work. Huff collected the samples and prepared their description. Lakin wrote the section concerning chemical analysis; and Myers wrote that on spectrographic analysis. Lovering made the statistical computations and wrote the sections covering distribution of copper and comparison of analytical methods. Jointly we have criticized and revised each other's work and agreed to the conclusions.

DESCRIPTION OF SAMPLES

The soil samples used in the investigation were collected near the Malachite mine in Jefferson County, Colo. Previous geologic and geochemical investigations made in this area by Huff (11) determined the distribution of copper in soil throughout the area and yielded other data of use in collecting the soil samples described here.

The soil samples can best be described in terms of the geologic setting of the ore deposits. The Malachite mine is in the Front Range of the Rocky Mountains about 12 miles west of Denver, Colo. It is on the north side of Bear Creek Canyon at an altitude of about 7,500 feet. Exposures of bedrock are numerous near the mine, but most of the land surface is covered with a thin residual soil. Part of the area is grassland, and part of it is covered by widely spaced pine trees and brushy thickets.

Precambrian quartz-biotite schist and hornblende gneiss constitute the bed rock close to the mine. Alternating layers of these rocks from 50 to several hundred feet in thickness and with a general easterly strike are cut by numerous pegmatitic dikes, which trend northeasterly. The hornblende gneiss and the pegmatite are particularly resistant to erosion. Gneiss and pegmatite form most of the local outcrops and the larger fragments in the soil.

The ore bodies are in an east-trending vein 50 to 100 feet wide that can be traced about 2,500 feet by means of outcrops, float, and scattered prospect pits. One ore body was discovered many years ago by tracing malachite-stained float to its source. This ore body and another discovered in 1940 are both irregular pipe-like masses within the vein. In both ore bodies chalcopyrite and pyrrhotite are the dominant sulfides, but galena and dark-brown sphalerite are also present. Many fragments of country rock and some vein quartz are present in the ore. Near the land surface the ore has weathered to an iron-stained gossan that locally has thin coatings of malachite on joint surfaces.

The soil is thin and rocky with poorly defined, but recognizable, soil horizons. The surficial dark-brown to black "A" horizon used in the chemical study averages only about 0.5 foot in thickness. It is underlain by a light-brown "B" horizon containing less organic material but more silt and clay. The "C" horizon, or weathered and softened bedrock, is at an average depth of only 2 to 3 feet.

The surficial soil has a wide range in copper content. Near the ore it contains more than 5,000 ppm (parts per million) copper, and on the hillside

above the ore, about 50 ppm. Geochemical mapping has demonstrated an anomaly 2,600 feet long and 900 feet wide that can be traced much farther downhill and slightly farther along the strike than can iron-stained gossan or other visible signs of mineralization. The highest concentrations occur near the mineralized zone, particularly near prospect pits and mine workings.

During preliminary geochemical mapping, some difficulty was experienced in obtaining consistent results. Difficulties manifested themselves as irregu-

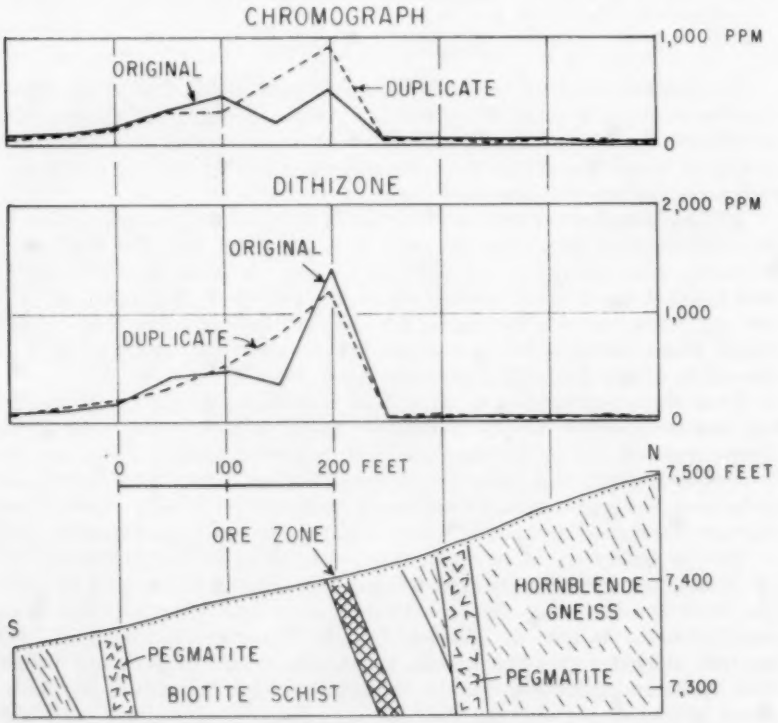


FIG. 1. Copper content along section across weakly mineralized vein, as determined by two different geochemical prospecting tests.

lar values that prevented the smooth contouring of the copper concentration in the soil and which could not be duplicated by repeated sampling and analysis. Along one traverse (Fig. 1), for example, only one vein is present, but the original chromographic set of analytical results indicated two small veins. Such difficulties naturally created doubts concerning the analytical method used and a desire for a better one.

To compare analytical methods quantitatively a special set of 104 samples was collected in duplicate from 52 sample points. Each sample consisted of

half a pint of the minus 80 mesh fraction of the surficial soil. An original and a duplicate sample were collected near each survey stake but about 2 feet apart. The duplicates simulate what might be expected from two independent surveys and samplings of the area. The samples were collected from four traverses crossing definite but relatively small anomalies more than 800 feet from ore. In copper content, these samples range from below 100 ppm, in samples from the hillside above the vein, to over 200 ppm in many samples collected near or downhill from the vein. The analyses of these samples as shown beyond are in a range well suited for statistical comparison of analytical methods.

GEOCHEMICAL PROSPECTING TESTS

The analytical methods used in geochemical prospecting are commonly much simplified procedures designed for the convenient analysis of many samples. In many published descriptions these methods have been called field tests to indicate that they can be performed wherever the sample is collected or in makeshift field laboratories. These methods also have been called rapid or semiquantitative tests. Here these methods will be called geochemical prospecting tests to differentiate them clearly from quantitative laboratory procedures. The geochemical prospecting tests used on our samples include five wet chemical methods and one spectrographic.

Most geochemical prospecting tests involve a digestion of the sample to put the ore metal in solution, and an estimation of the amount of metal by development of a characteristic color of solution or spot that is compared with the color of standards. The tests differ considerably in intensity of the digestion and portability of equipment. The cold citrate soluble method can be used at the sample site to detect the metals that are readily soluble. Greater solution is attained in hot digestions designed for use at camp sites or field laboratories. Both the heavy metal and the dithizone tests use a hot acid digestion. The chromographic and biquinoline tests, utilizing a bisulfate or pyrosulfate fusion, and the semiquantitative spectrographic methods detect essentially all of the copper present.

Brief descriptions of these tests are given here only to indicate their general nature. Anyone desiring to perform such analyses should consult the original published description. The original published descriptions also can be consulted for the quantitative spectrophotometric laboratory procedure (1) and the quantitative spectrographic procedure (4) used for comparison.

Citrate Soluble Heavy Metal.—This rapid semiquantitative method devised by Bloom (5) for estimation of readily soluble copper, lead, and zinc in soils and sediments requires the following procedure: About 0.1 g of sample, measured approximately with a small scoop, is placed in a glass-stoppered cylinder along with the ammonium citrate buffer, hydroxylamine hydrochloride, and 1 ml of dilute solution of dithizone in xylene and shaken vigorously for 5 seconds. The green-colored dithizone changes through bluish purple to red as it reacts with the heavy metals; the amount of heavy metals is measured by the volume of dithizone solution required to produce the bluish purple color. The method has been widely used in geochemical

exploration, particularly on stream sediments. It is, of course, a measure of only that small part of the metal which is soluble in the citrate solution. This method can be used at the sample site, and about 200 determinations can be made per man-day.

Heavy Metal.—This procedure devised by Huff (10) is briefly as follows: One-third gram of sample is boiled in dilute nitric acid for one hour. An aliquot of this sample solution is added to a sodium acetate-ammonium fluoride buffer and shaken with 5 ml of a dilute solution of dithizone in carbon tetrachloride. The metal content of the sample is determined by comparing the color obtained in the carbon tetrachloride layer with the color of similar layers prepared by using standard solutions. The hot nitric acid extraction removes the copper that is present in many copper minerals and also that adsorbed on the surface of clay minerals; it does not attack most silicates. Under the conditions of the test the major elements that react with the dithizone solution are copper, lead, and zinc. The test is easy to perform in a makeshift field laboratory; simple apparatus and reagent grade chemicals are required; and an experienced technician can make about 150 tests per day.

Chromographic Copper.—In this procedure of Stevens and Lakin (16) 0.1 g of soil is fused with 0.5 g of potassium bisulfate. The cold fused mass is disintegrated in sodium citrate solution; the solution is made just alkaline, and then made acid with acetic acid. An aliquot of this solution is placed in a "chromograph" or confined-spot test apparatus and permitted to flow slowly through filter paper impregnated with rubeanic acid. The gray to black spot formed is compared with a series of standard spots prepared similarly and the copper content is estimated. Experience with the method indicates that some workers tend to become careless with rate of flow control and obtain poor results. Under field conditions 80 or more determinations can be made per man-day.

Dithizone Copper.—The procedure of Almond and Morris (2) briefly is as follows: One gram of finely powdered sample is digested in 30 ml of 1 N sulfuric acid, and 2 ml of the cooled supernatant liquid is transferred to a 10 ml graduated glass cylinder. Ammonium citrate solution is added to the aliquot, and the solution adjusted to a pH between 2.5 and 3 with ammonium hydroxide by use of thymol blue as an indicator. A .001 percent fresh solution of dithizone in carbon tetrachloride is added and the mixture is shaken for 2 minutes. The mixed color obtained is compared with standard solutions to estimate the amount of copper present.

The method was developed to estimate the acid soluble copper that was introduced into altered igneous rocks by spent fluids from ore forming solutions; it has also given satisfactory results with soils. The method is suitable for camp-site use, requiring simple equipment and reagents. Under field conditions 90 or more determinations can be made per man-day.

Biquinoline Copper.—In this procedure of Almond (1) about 0.1 g of the finely powdered sample is fused with 0.5 g of potassium pyrosulfate in a culture tube. To the cool melt, 3 ml of 6 N hydrochloric acid is added and the tube is heated in a boiling water bath until the melt disintegrates; then

the solution is diluted to 10 ml and mixed. In a clean test tube a clear aliquot of the solution is mixed successively with hydroxylamine hydrochloride, tartrate-acetate buffer, and an isoamyl alcohol solution of 2,2′-biquinoline. After shaking the pink color developed in the isoamyl alcohol layer is compared with standards similarly prepared. The standards are semipermanent and can be used for approximately a month. The bisulfate fusion attacks many silicates and is quite effective in rendering most copper minerals soluble. The biquinoline reagent is more stable than dithizone and therefore more satisfactory for general use. The procedure permits the determination of copper in about 100 samples per man-day under field conditions.

SPECTROGRAPHIC ANALYSIS

The spectrographic analyses were made using an emission spectrograph of the grating type. The equipment and procedure for the semi-quantitative or geochemical prospecting test is the same as that used for quantitative spectrographic analysis (4) except for a visual rather than densitometer comparison of sample spectra with standard spectra (6). The standards for the semiquantitative analysis contain copper in concentrations of 1.00, 0.464, 0.215, 0.100...percent and the results are reported by midpoint of the class interval as 0.7, 0.3, 0.15...percent. About 20 samples with about 10 determinations in each sample can be made per man day.

In comparison with the wet chemical methods, spectrographic methods are relatively expensive for making one determination but relatively cheap for many determinations in each sample. In the United States, spectrographic methods are used in geochemical prospecting chiefly to supplement wet methods by determining what elements are associated with the principal ore metals. In Russia, in Canada, and in several other countries, however, spectrographic methods are used much more extensively in routine geochemical prospecting.

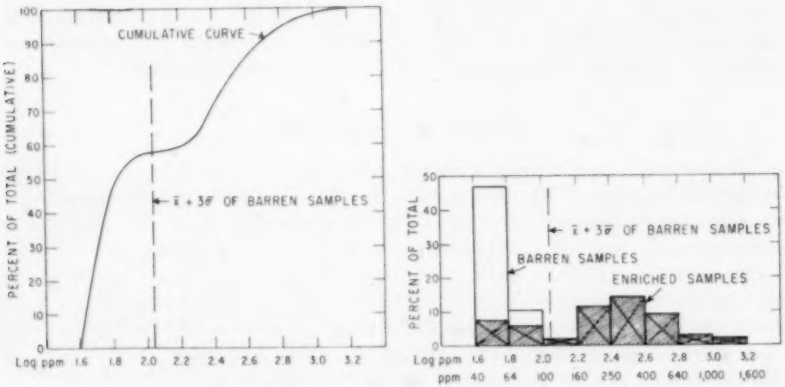
STATISTICAL DISTRIBUTION OF COPPER

The concentration of copper in the 104 soil samples as determined by quantitative analysis ranges from 50 ppm in several samples to 1,300 ppm in one sample. In order to investigate the copper-frequency distribution we must first sort the data into convenient class intervals.

The selection of appropriate class intervals involves several problems. The class intervals chosen should be related to the figures used in reporting the analyses and should have a simple, consistent relationship to each other. Subdividing the data into equal arithmetic class intervals presents us with a difficult choice. If the classes are made small enough to indicate the way the bulk of the samples are distributed in the low concentration range, the number of classes needed to cover the whole range becomes prohibitively large and we have a number of vacant classes. If, on the other hand, we increase the class interval enough to reduce the number of classes to a reasonable figure and eliminate the vacant classes, the interval becomes so large that most of our samples of low concentration fall in a single class. We have,

therefore, used logarithmic class intervals to give better discrimination in the low concentration range and to cut down scatter in the higher concentrations.

A histogram and cumulative distribution curve has been prepared for all samples using logarithmic class intervals (Fig. 2). This distribution is distinctly bimodal, with one mode in the 40 to 100 ppm range and the other


CUMULATIVE CURVE
PERCENT OF TOTAL (CUMULATIVE)
$\bar{x} + 3\bar{\sigma}$ OF BARREN SAMPLES
Log ppm 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2
PERCENT OF TOTAL
$\bar{x} + 3\bar{\sigma}$ OF BARREN SAMPLES
BARREN SAMPLES
ENRICHED SAMPLES
Log ppm 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2
ppm 40 64 100 160 250 400 640 1,000 1,600

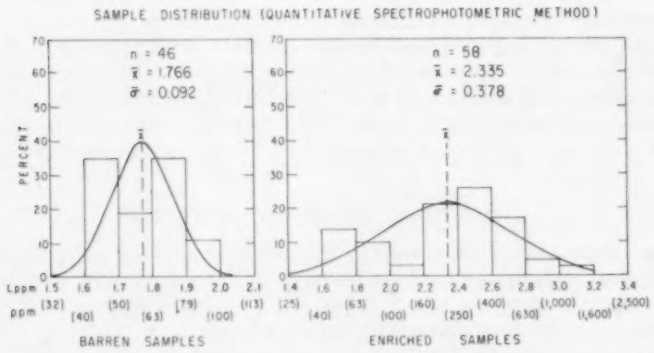

SAMPLE DISTRIBUTION (QUANTITATIVE SPECTROPHOTOMETRIC METHOD)
n = 46
$\bar{x}$ = 1.766
$\bar{\sigma}$ = 0.092
PERCENT
Lppm 1.5 1.6 1.7 1.8 1.9 2.0 2.1
ppm (32) (40) (50) (63) (79) (100) (113)
BARREN SAMPLES
n = 58
$\bar{x}$ = 2.335
$\bar{\sigma}$ = 0.378
1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2 3.4
(25) (40) (63) (100) (160) (250) (400) (630) (1,000) (1,600) (2,500)
ENRICHED SAMPLES

FIG. 2 (upper). Frequency distribution of copper assays, Malachite mine area.

FIG. 3 (lower). Frequency distribution of copper in samples from barren and enriched soil.

in the 250 to 400 ppm range. The cause of this bimodality is readily apparent. Our samples include some from barren soils uphill from the ore body and some from enriched soils over and below the ore body. The bimodal distribution results from the mixing of two populations, one with copper values characteristic of soil from barren rock and one with copper values enriched by copper from ore. This distribution exhibits a pronounced bench

in the cumulative curve corresponding to the low intramodal class. The dividing line between barren samples and ore samples is about 100 ppm and we might safely use this value to distinguish between enriched and barren copper assays. It is important that we know this value because analytical procedures can be arranged so that they can best distinguish between samples over and those under the critical value.

In order to compare and contrast these distributions we can split the total sample group into two subgroups consisting of samples taken from barren soils uphill from the ore body and samples from the enriched soils over and downhill from the ore body. Histograms for each subgroup are given here along with normal distribution curves calculated from the mean and standard deviation for each subgroup (Fig. 3). Since the classes are logarithmic these are log normal distribution curves. For a normal dis-

TABLE 1

COMPARISON OF ACTUAL AND PREDICTED DISTRIBUTIONS OF BARREN SAMPLE VALUES AND ORE SAMPLE VALUES

Barren samples	Observed (percent)	Predicted (percent)
$\bar{X}$ = 1.766 (58 ppm)		
$\bar{X} \pm \bar{\sigma}$ = 1.67–1.86 (47–72 ppm)	72	68
$\bar{X} \pm 2\,\bar{\sigma}$ = 1.58–1.95 (38–89 ppm)	100	95
$\bar{X} \pm 3\,\bar{\sigma}$ = 1.49–2.04 (31–112 ppm)	100	99 3/4
Ore samples		
$\bar{X}$ = 2.335, (216 ppm)		
$\bar{X} \pm \bar{\sigma}$ = 1.96–2.71 (91–520 ppm)	66	68
$\bar{X} \pm 2\,\bar{\sigma}$ = 1.58–3.09 (38–1,230 ppm)	98	95
$\bar{X} \pm 3\,\bar{\sigma}$ = 1.20–3.47 (16–2,945 ppm)	100	99 3/4

tribution about 68 percent of the sample values fall within one standard deviation of the mean, 95 percent within two standard deviations and 99¾ percent within three standard deviations. The figure shows discrepancies between the actual distribution and this theoretical distribution but a comparison of the observed distributions with that predicted on the assumption of a normal distribution (Table 1) shows pretty good overall agreement.

The predictions are close enough to encourage further predictions on the basis of the normal curve. The two distributions overlap in such a way that there is only about 1 chance in 40 that a sample of 90 ppm or more will come from the barren population, whereas a sample of 90 ppm or less has a chance of 1 in 6 of coming from the ore population. In other words a sample low in copper could have come from either population, but any sample containing 90 ppm or more probably came from the ore population.

Our data is similar in many respects to data obtained in geochemical prospecting studies made elsewhere. After studying sets of analytical data involving the analysis of thousands of samples of soils from mineralized areas Tennant and White (17) conclude that the distribution of metal is commonly a mixture of two log-normal distributions, one representing the background, and the other, the anomaly; they describe a method utilizing probability

paper whereby the two distributions can be distinguished. In rock near the Franklin-Sterling ore deposits and in soil near a mine in Pennsylvania (17), as at the Malachite mine, the distribution with the higher average and the greater standard deviation is spatially related to ore.

COMPARISON OF ANALYTICAL METHODS

The cost of analytical methods for geochemical prospecting is an important consideration in their selection. Geochemical prospecting requires the analysis of many samples and costs are sufficiently important to justify estimates, even though the basic data is not all that might be desired. Estimates given here (Table 2) are based upon the man hours of analyst's time required to analyze 100 samples. Most of the geochemical prospecting tests require less than 10 hours for 100 samples, which is much less than the quantitative methods.

TABLE 2

APPROXIMATE COST OF GEOCHEMICAL PROSPECTING TESTS IN TERMS OF MAN HOURS OF ANALYST'S TIME

Method	Hours required to analyze 100 samples
Citrate soluble	4
Heavy metal	5 1/2
Biquinoline copper	8
Dithizone copper	9
Chromographic copper	10
Semiquant. spectrographic*	40
Quant. spectrophotometric	40
Quant. spectrographic*	160

* It should be noted that 10 elements can be determined spectrographically in little more time than required for 1 and that spectrographic methods compare more favorably when several determinations are required for each sample.

The value of an analytical method in terms of its ability to give the desired results is less easy to determine. How good a method is depends upon three factors: 1) how well the method indicates minor variations in the concentration of the element sought; 2) how well duplicate analyses by the same method agree with each other; and 3) how closely an analysis agrees with the accepted value for concentration of the element present in the sample. Here we call these factors respectively: discrimination, precision, and accuracy.

The discrimination of a method, as we use the term, indicates the number of categories by which analyses can be expressed. The semiquantitative spectrographic results, for example, are commonly reported by the U. S. Geological Survey laboratory as 15, 30, 70, 150 ppm, etc., so that there are just three categories for a tenfold difference. The other extreme is the quantitative spectrographic method with values reported as 10, 11 ... 52, 53, ... etc. so that there may be as many as 90 categories for a tenfold difference. The semiquantitative spectrographic method groups definitely abnormal samples containing 100 ppm with background samples containing 50

ppm; if this method used six categories instead of three for tenfold differences, its usefulness in geochemical prospecting would be enhanced. A high discrimination becomes objectionable, however, when the figures reported suggest greater accuracy than is actually obtained. Studies of standard rock analysis indicate that measurement of constituents like silica which are given to 0.01

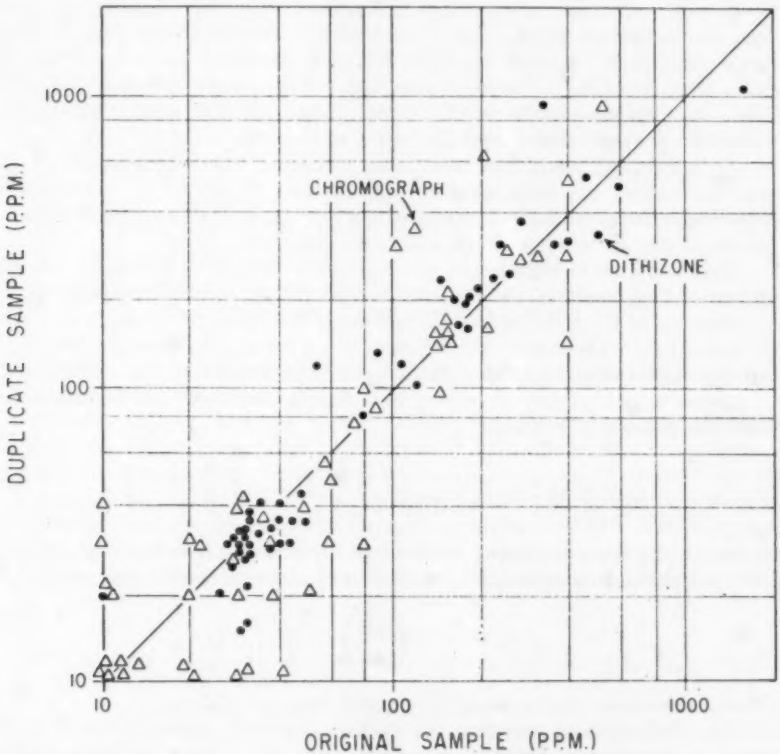


FIG. 4. Scatter diagram showing precision of geochemical prospecting tests.

percent are commonly in error by 0.1 percent (13). To avoid both objectionable extremes, the discrimination of a method should be related to both its precision and accuracy.

As usually interpreted the precision of an analytical method is a measure of the deviation between replicate determinations on splits of the same sample. In geochemical prospecting, however, we are often more interested in precision of the entire sampling and analytical process. For this reason we use precision to indicate the deviation between determinations on replicate samples.

The evaluation and comparison of relative precision of various analytical

methods can be done in a number of different ways. One of the simplest ways of comparing the precision of different methods is by the use of a scatter diagram with the concentration laid out along both X and Y axes. For each sample pair one dot is plotted with the abscissa indicating the original and the ordinate the replicate analysis so that the dots are scattered along a diagonal line. Using a scatter diagram, it is easy to see that the dithizone has better precision than the chromograph method (Fig. 4). Scatter diagrams have the advantage of allowing a quick visual estimate of the concentration range that gives optimum precision for each analytical method, as well as permitting estimates of over-all precision. The scatter diagram technique works best on moderately small sample groups (20–50) with concentration values fairly evenly distributed through a wide range.

An alternative method of measuring precision, based upon ratios of the replicate values, has been used by Hawkes and Bloom (9). These ratios can be cumulated and the cumulative curves for several analytical methods can be plotted on a single graph and easily compared.

Here we wish to experiment with a rigorous statistical technique, the coefficients of variation of the replicate values (15, p. 44). The coefficient of variation (C of V) is defined as the quotient of the standard deviation (s) over the mean ($\bar{x}$). The lower the coefficient of variation, the better the precision. Absolute agreement on all duplicates would give a C of $V = 0$. For a pair of sample values, A and B, where $A < B$ this coefficient can be calculated from the following formula:

$$C \text{ of } V = \frac{s}{\bar{x}} = \frac{\sqrt{2[1/2\,(B-A)]^2}}{1/2\,(B+A)} = \sqrt{2}\left(\frac{B-A}{B+A}\right)$$

For example, suppose copper analyses of replicate samples gave 20 and 30 parts per million respectively, the coefficient of variation for this pair would be:

$$C \text{ of } V = \sqrt{2}\left(\frac{10}{50}\right) = \frac{\sqrt{2}}{5} = 0.28$$

These calculations can be readily computed on a calculator.

The coefficients of variation for various analytical methods can be compared as cumulative distribution curves (Fig. 5). Some of these curves have a smooth rise and some have a marked bend in them. In general the curves with a high initial point followed by a very flat slope through several class intervals reflect methods with a coarse reporting interval (i.e., the semiquantitative spectrographic method). The biquinoline and dithizone copper are good in that 80 percent of the replicates had coefficients of variation of less than 0.15.

The precision of an analytical method commonly depends in part upon concentration. As indicated previously we are particularly interested in precision in the 100 to 320 ppm range. This range and others can be investigated separately by averaging the coefficient of variation in each range. The result shows (Table 3) that, among the geochemical prospecting tests the

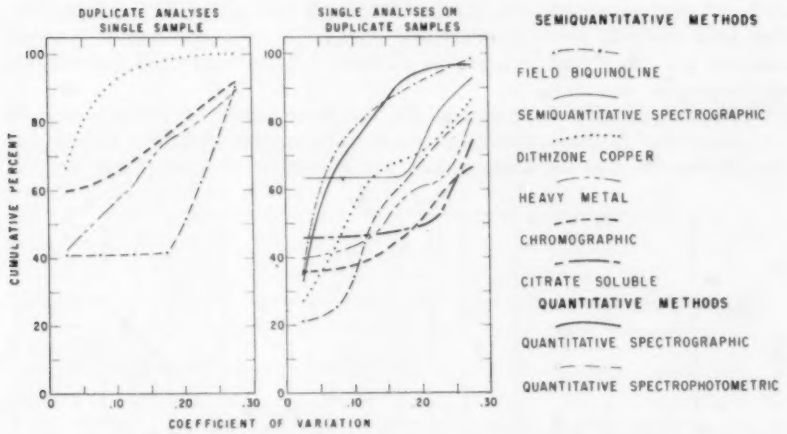


FIG. 5. Cumulative frequency distribution curves for coefficients of variation showing precision of geochemical prospecting tests.

biquinoline and the dithizone copper have the lowest coefficient of variation in the critical 100 to 320 ppm range.

The evaluation of accuracy is more difficult than the evaluation of precision, because absolute accuracy can be determined only by reference to the exact copper concentration in our samples—which is unknown. The best we can do is to determine relative accuracy of the geochemical prospecting tests by comparison with the best quantitative method available. In this investigation we could have used either the quantitative spectrophotometric (1) or the quantitative spectrographic method (4) as a standard of comparison. The

TABLE 3

AVERAGE COEFFICIENT OF VARIATION OF COPPER ANALYSIS OF REPLICATE SOIL SAMPLES FROM THE MALACHITE MINE AREA

[Coefficient of variation stated as a decimal fraction = %/100]

Method	Concentration range (ppm)			
	Under 100	100 to 320	Over 320	All samples
Quantitative spectrophotometric	0.07	0.08	0.15	0.09
Quantitative spectrographic	.09	.10	.14	.10
Semiquantitative spectrographic	.05	.18	.10	.11
Dithizone copper	.17	.11	.21	.14
Biquinoline copper	.18	.14	.20	.17
Heavy metal	.38	.16	.12	.23
Citrate soluble	—	.19	—	—
Chromographic copper	.25	.20	.37	.28

chemical method was chosen, partly because all but one of the semiquantitative field methods were chemical and partly because quantitative chemical analyses are more readily available to most investigators than quantitative spectrographic analyses.

The accuracy can be evaluated by the same statistical techniques used for precision. A qualitative comparison using scatter diagrams shows that the biquinoline and dithizone values are systematically low (Fig. 6). A

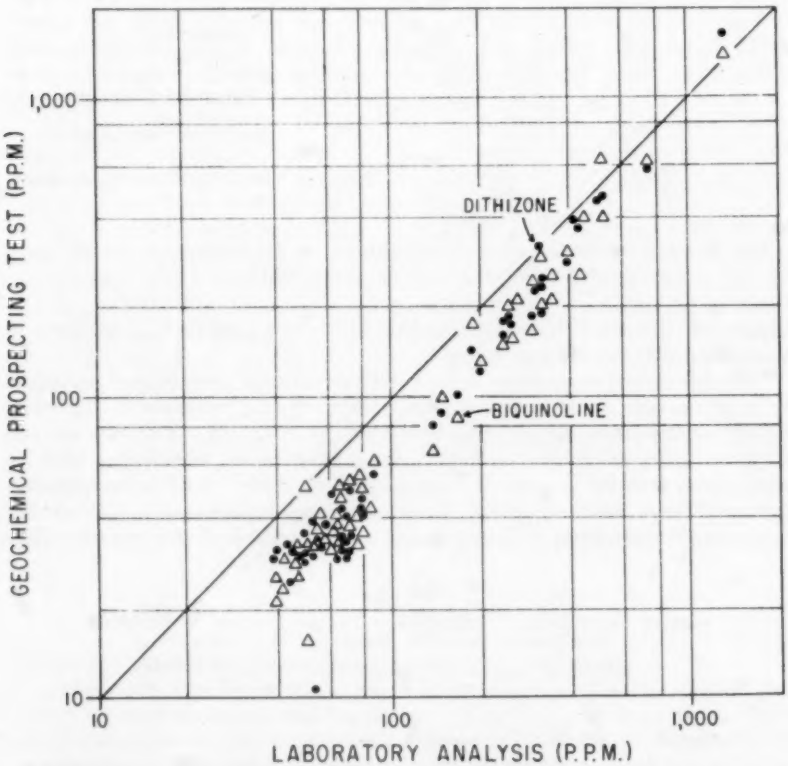


FIG. 6. Scatter diagram showing accuracy of geochemical prospecting tests.

quantitative comparison based upon coefficients of variation between the prospecting test and the quantitative analysis (Fig. 7; Table 4) shows the semiquantitative spectrographic method to have the lowest coefficient of variation in the critical 100 to 320 ppm range. The biquinoline, dithizone, and heavy metal methods are less accurate in the critical range than the spectrographic method but more accurate than the citrate soluble heavy metal and the chromograph test for copper.

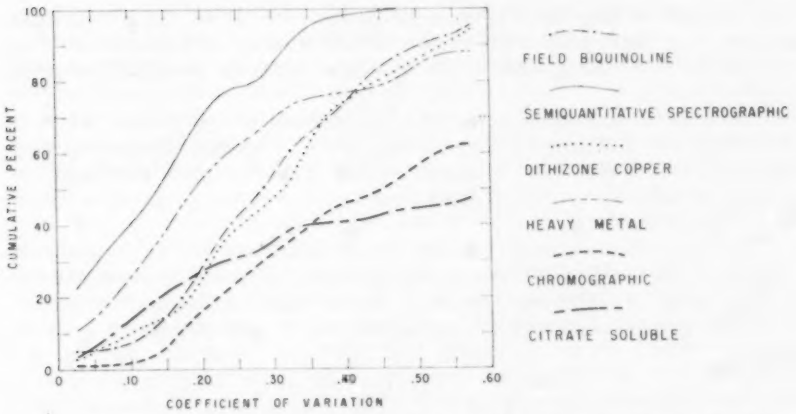


FIG. 7. Cumulative distribution curves of coefficients of variation showing accuracy of geochemical prospecting tests.

Systematically low results (Fig. 6) show that the low accuracy of some of the methods probably is caused by incomplete digestion. The samples contain small amounts of copper in fragments of hornblende and other minerals that do not dissolve in the dilute acid digestant of the geochemical prospecting test but are detected in the quantitative analysis. This incomplete solution of copper affects accuracy but is not necessarily disadvantageous for geochemical prospecting because the amount of copper in the hornblende may have no relation to proximity to ore. Although this factor may be important we will make no further attempt to evaluate it for present purposes.

DISCUSSION OF RESULTS

Our primary objective is to choose by statistical methods the best geochemical prospecting test for use in the Malachite area. As several factors

TABLE 4

AVERAGE COEFFICIENT OF VARIATION OF GEOCHEMICAL PROSPECTING TESTS VERSUS QUANTITATIVE ANALYSIS OF SOIL SAMPLES FROM THE MALACHITE MINE AREA

[Coefficient of variation stated as a decimal fraction = %/100]

Method	Concentration range (ppm)			
	Under 100	100 to 320	Over 320	All samples
Semiquantitative spectrographic	0.18	0.12	0.14	0.17
Heavy metal	.28	.34	.18	.29
Biquinoline copper	.38	.26	.16	.32
Dithizone copper	.44	.27	.13	.33
Chromographic copper	.63	.45	.26	.53
Citrate soluble	—	.64	.31	.56

are involved in the choice some assumptions have to be made concerning their relative importance. To simplify the discussion it is assumed here that the factors cost, discrimination, precision, and accuracy should all be given equal weight.

The cost of analysis in terms of analysts' time ranges from 4 hours to 160 hours for 100 samples. If we rank the geochemical prospecting tests in terms of cost they are: 1. citrate soluble, 2. heavy metal, 3. biquinoline copper, 4. dithizone copper, 5. chromographic copper, and 6. semiquantitative spectrographic.

The methods vary in discrimination but differences can be judged only roughly. The geochemical prospecting tests can be ranked in about the following order: 1. dithizone copper, 2. heavy metal, 3. biquinoline copper, 4. chromographic copper, 5. citrate soluble, and 6. semiquantitative spectrographic.

TABLE 5

COMBINED EVALUATION OF VARIOUS ANALYTICAL METHODS

[Ranked from 1 = best to 6 = worst]

Method	Cost	Discrimination	Precision		Accuracy		Total
			Total range	100–320 ppm	Total range	100–320 ppm	
Dithizone copper	4	1*	2	1	4	3	15
Biquinoline copper	3	3*	3	2	3	2	16
Heavy metal	2	2*	4	3	2	4	17
Semiquantitative spectrographic	6	6*	1	4	1	1	19
Citrate soluble	1	5*	5*	5	6	6	28
Chromographic copper	5	4*	6	6	5	5	31

* Estimated values.

When we evaluate the various methods in terms of precision, we must decide whether over-all precision throughout the total concentration range covered by the analyses or relative precision through the critical range of 100–320 ppm is most important. The methods ranked in order of over-all precision are: 1. semiquantitative spectrographic, 2. dithizone copper, 3. biquinoline copper, 4. heavy metal, 5. citrate soluble, and 6. chromographic copper. Ranking in order of relative precision over the important 100–320 ppm concentration range places the methods in this sequence: 1. dithizone copper, 2. biquinoline copper, 3. heavy metal, 4. semiquantitative spectrographic, 5. citrate soluble, and 6. chromographic copper.

In a similar manner we may rank the various methods with respect to their accuracy relative to the quantitative spectrophotometric method. These data are summarized in the following table (Table 5).

If each of the above criteria is given equal weight in evaluating the various analytical methods, the methods having the lowest total number in Table 5 are the best. It appears that the dithizone and biquinoline geochemical pros-

pecting tests are the best; the heavy metal and the semiquantitative spectrographic methods are intermediate; and the chromographic copper and citrate-soluble methods are poorest. Actually the factors of cost, discrimination, and precision would probably be weighed more heavily, so that the choice from the statistical evaluation would lie between the dithizone copper and biquinoline copper methods with the dithizone slightly favored over biquinoline.

The results can be checked qualitatively by their agreement with geologic details. Along the section (Fig. 1) copper in the soil is derived chiefly from the copper-bearing vein. The soil overlying the vein is a mixture of materials derived from the vein and from the barren country rock which have been moved downhill by gravity and mixed together during the weathering process. From these geologic relations we can anticipate a copper anomaly which is low uphill from the vein, reaches a high immediately over the vein, and gradually decreases downhill. The graphs of Figure 2 show that not only do the dithizone values agree better with each other than do the chromographic values but they are in closer agreement with the known position of the vein.

Although the dithizone geochemical prospecting test proved to be the best for the Malachite area it may not be the best for prospecting for copper in other areas. During hot weather the greater stability of the biquinoline reagent makes it preferable to dithizone for camp site use. In an area where a relatively low order of precision is tolerable and where lead and zinc are of interest as well as copper the heavy metal method may be preferable. The semiquantitative spectrographic method will give information on a wider range of ore metals. In regional field reconnaissance, where the objective is to locate favorable areas rather than to pinpoint ore bodies, the citrate soluble method may be most useful because of its simplicity and amenability to use at the sample site. However, in any area a statistical comparison of available methods should prove useful.

U. S. Geological Survey,
Denver, Colo.,
Nov. 14, 1960

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BEDDED PYRITE AND MICRO-ORGANISMS FROM THE MOUNT ISA SHALE

L. G. LOVE AND D. O. ZIMMERMAN[1]

CONTENTS

PAGE

Abstract 873
Introduction—General 874
The Mount Isa Shale 874
Mineralization at Mount Isa 875
Micro-organisms and syngenetic iron sulfide 875
Results of New Work 876
Bedded pyrite of the Northern Leases, Mt. Isa 876
Sulfide content of bedded pyrite layers 880
Pyrite 880
Other sulfides 880
Zoning structures of the pyrite-I 881
Isolation of the micro-organisms 883
Preparation of the pyrite concentrate 883
Oxidation of the pyrite concentrate 884
Visual and other checks on results 884
Description of the micro-organisms 885
Sulfur isotopes 886
Discussion 886
Pyrite-I grain zoning and the micro-organisms 886
Relation of grain zoning to atoll structures 887
"Syngenetic" origin of the bedded pyrite 888
Environment and role of the micro-organisms 889
Origin of the massive sulfides 892
Summary and conclusions 892
Acknowledgments 893
References 893

ABSTRACT

The origin of the first generation pyrite of the Lower Proterozoic Mount Isa Shale of Australia is considered to be syngenetic rather than epigenetic. It is shown that the pyrite grains occur as infillings of a hitherto unknown type of fossil micro-organism whose relic form is related to the zonal structure found in the grains. The micro-organisms are analogous to forms of Paleozoic and Mesozoic age that are characteristic of sapropelic black shales. To the micro-organisms is attributed the formation of the iron sulfide syngenetically with the deposition of the enclosing sediment or during the earliest period of diagenesis.

[1] B.M.R., Australia. Permission to publish given by the Director, Bureau of Mineral Resources, Geology and Geophysics, Canberra, Australia.

INTRODUCTION

THIS paper is presented to acquaint economic geologists with a previously unrecognized association between micro-fossil remains and a well known ore deposit in the hope that it may lead to a more widespread consideration of the genetic significance of the principles involved.

The first author is a paleontologist and, while studying some of the micro-organisms characteristic of bituminous and carbonaceous shales of various post-Cambrian ages, has been enquiring into some aspects of the environment of deposition of such rocks. The second author is at present making a study of mineralization at the Northern Leases, in the Mount Isa area of Queensland, Australia. It was felt that a combined application of the specialities involved would be of value and a joint study has therefore been made of one of the problems concerning the Precambrian ore deposits around Mt. Isa, viz., that of the origin of the first generation pyrite.

The Mount Isa Shale

Mount Isa is situated in the north west corner of Queensland, Australia, and its area comprises rocks mainly of Precambrian age including the Mount Isa Shale, which contains rich copper and lead-zinc ore bodies. The Mount Isa Shale occurs as the eastern limb of a northerly pitching syncline and dips steeply westward with a little internal folding. Its strike length is about 30 miles north to south but it is rarely more than 3 miles wide. The western limb of the fold is faulted and sheared out, and the Shale is thus brought into contact with more highly metamorphosed shales and quartzites that rest against granite 4 miles or more from the fault. The Shale has suffered only mild metamorphism in contrast with the adjacent rocks on which it rests unconformably except when faulted out. A Lower Proterozoic age has been attributed by Carter (7, 41) to these rocks, and other members of the group containing the Mount Isa Shale are, not far to the west, overlain unconformably by arenaceous beds assigned to the Upper Proterozoic. The latter are unconformably overlain by almost flat lying members of the fossiliferous Middle Cambrian series.

Rocks of Lower Proterozoic age in the area are known to contain primitive life forms, although no extensive search for the presence of micro-organisms has yet been made. Blanchard and Hall (5, p. 1047) quote evidence of distinguishable macro-organisms in the Mount Isa Shale and noted that the rock provided a very favorable environment for the preservation of fossils.

The upper portion of the Mount Isa Shale has been subdivided as below (23, p. 354) with the average thicknesses as listed:

upper—hard siliceous shale	700 feet
middle—dolomitic shale	1,600 feet
lower—siliceous thin bedded shale and soft argillites	5,000 feet

The grouping includes a diversity of lithologies ranging from fine conglomerate to claystone and dolomitic types (7), but most common are thin

bedded siltstones and shales with pyritic and carbonaceous bands and, locally, carbonate in excess of 20 percent.

The beds containing the fine grained pyrite also enclose lead-zinc mineralization in three areas near the top of the thin bedded shale group. These areas are at Mount Isa itself, where copper also occurs, the Northern Leases, and an area 13 miles to the south of Mount Isa. The pyritic beds would, however, appear to be more extensive and may continue over the whole outcrop length of the Mount Isa Shale. S. R. Carter (9, p. 366) reports that the pyrite mineralization extends north and south along the bedding planes far beyond the limits of economic mineralization and "weakly for several miles"; further, in a personal communication he notes that it occurs with weak sphalerite mineralization in the only two drill holes on the 10 miles of strike length separating the Northern Leases from Mount Isa. This indicates that the present study of pyrite from the Northern Leases is directly applicable to that at Mount Isa. In addition, Knight (24, p. 812) reports the Shale to be pyritic in the area 13 miles to the south of Mount Isa.

Sedimentary structures have been recognized in the Mount Isa Shale and these include cross bedding (indicating that the beds are not overturned) and slump structures with associated breccias. Some differences of opinion on the validity of the slump forms has recently been presented in this Journal (39, 40, 27) but E. K. Carter (7) and S. R. Carter (personal communication) affirm their presence in the field.

Mineralization at Mount Isa

The bedded replacement type mineralization at Mount Isa has been adequately described (17, 30, 6, 8, 9) and remarks concerning the lead-zinc ore bodies are applicable generally to the lead-zinc occurrence at the Northern Leases. The bulk of the work already done has been concerned with the complex mineralogy and paragenesis of the economic lead-zinc and copper lodes, with particular attention to the massive replacement features of the orebodies. For the main purposes of this paper, however, attention may be restricted to the pyrite in the shales occurring with, and extending beyond, the economic orebodies. This pyrite is the first sulfide in the paragenetic sequence (i.e. pyrite-I) and is followed by lesser pyrite, quartz, carbonate, and a host of sulfides of which sphalerite and galena are the most abundant. The latter two partially replace some of the grains of pyrite-I to form atoll structures (35, 37).

Micro-organisms and Syngenetic Iron Sulfide

The pyrite-I, referred to here, includes that form of pyrite noted by Grondijs and Schouten (17, p. 415) as 'type *a*, a very fine grained "spherical pyrite," grain size 0.025 mm. to 0.005 mm., mostly with concentric zonar structure' and is a type well known in many deposits. In a number of these, as at Mount Isa, it has been shown to have acted as host to many varieties of replacement, all of which can be traced back to the original spherical form

of pyrite (35). At Mount Isa framboidal texture such as is found in spherical pyrite of the Kupferschiefer of Germany, has been noted as absent by Schouten (35, p. 376). Possible examples of this texture revealed by etching are noted later in this paper. In both deposits, however, Grondijs and Schouten (17) and Schouten (36) allow that the pyrite spheres, as the first sulfide in the paragenetic sequence, may have been syngenetic with the deposition of the shale, and were certainly earlier than the main metasomatic processes that produced the other sulfides.

In the Kupferschiefer the spherical aggregates of various sulfides, among them pyrite, were regarded by Schneiderhöhn (34) and Neuhaus (28) as "mineralized bacteria." That the copper and lead ores were formed in this way was strongly disputed by Schouten (36) who indeed also preferred a primary inorganic rather than a biogenic origin of the iron sulfide as colloidal blobs. These theories were noted by Love (26), and followed by a demonstration that pyrite bodies of similar appearance from Lower Carboniferous shales of Scotland contained fossil micro-organisms. These were of a type not known hitherto, and not found by the author in an unpyritized condition, i.e. lacking pyrite, in any rock.

The pyrite was regarded as having been formed syngenetically with respect to the deposition of the subaqueous sediment, or possibly at a shallow depth in the still unconsolidated mud. The constancy of the peculiar association of the pyrite with the organisms was held to imply a probable bio-genetic relationship between them. The frequency of this micro-spherical type of sulfide, in sedimentary rocks of the dark shale type, has been noted by Deans and Eagar (in 13) and Deans (in 26, p. 437) and also by the first author who hopes subsequently to publish details of micro-fossils associated in this particular way with pyrite in many typical Palaeozoic and Mesozoic dark shales. In view of this, the continuation of such observations in the Proterozoic as in this paper is not surprising, and they will probably prove more common as work continues.

RESULTS OF NEW WORK

Bedded Pyrite of the Northern Leases, Mt. Isa

This form includes Grondijs and Schouten's (17, p. 415) types *a*, *b*, and *c* and the early pyrite of Carter (9, p. 366) from Mount Isa. A brief description of the occurrence of these types at the Northern Leases is given below.

The bedded pyrite of the first generation of mineralization, pyrite-I, occurs as very fine spherical to sub-spherical granules 2–4 microns in diameter, densely packed along particular thin sedimentary beds (Fig. 1). Less commonly it occurs as isolated grains arranged in a random scatter pattern or in ragged clusters of spherules not more than 2 mm wide (Fig. 2). The principal grain shape for the first generation is spherical but subhedral to euhedral crystalline forms also occur, and an outer growth zone around a spherical or cubic form may result in ragged irregular shapes. The euhedral

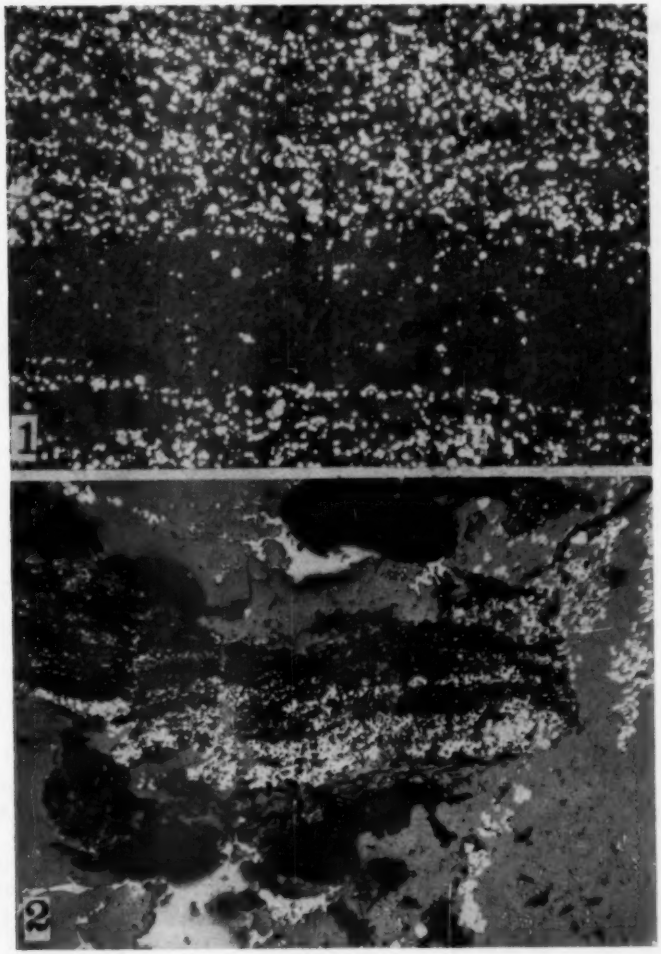


FIG. 1. Bedded pyrite-I (white) in shale (gray). × 150.
FIG. 2. Aggregated pyrite spheres. In oil × 1,350.

forms are most common where recrystallization of the pyrite has taken place, especially in close proximity to more massive sulfides including later pyrite.

The pyrite beds vary in thickness from the diameter of a single spherule to a rare 4 mm., and the boundaries, though sharp in hand specimens, are commonly diffuse under high magnifications. In fresh drill cores the pyritic beds have a distinctive chocolate brown color. Where later pyrite has been precipitated within the beds, with or without recrystallization of the earlier

pyrite, the beds may be several centimeters thick, with included lenses of shale constituents.

The pyrite beds act as sedimentary units, intimately paralleling bedding through fold and fault structures (17, figs. 1–25). The pyrite spherules behave as passive sedimentary grains within the pyrite beds; when they do occur en masse outside these, it is as a result of beds having been broken or replaced by later sulfides, so releasing some of the pyrite spherules as unreplaced grains in the massive sulfides. A few slivers of shale containing pyrite-I grains are found completely immersed in massive sulfides that crystallized later (Fig. 3).

The size, shape and aggregation characteristics of the pyrite-I grains were measured using statistical methods. The mode of the grain size is 2 to 4 microns (Fig. 25). The other characters (Fig. 4) were measured on grains in two widely separated thin beds, and for each bed separate esti-

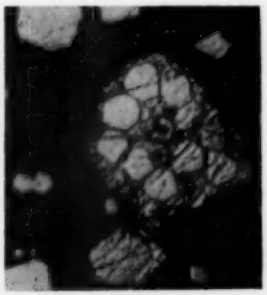


FIG. 3. Pyrite-I in shale (black) enclosed in sphalerite (gray) and some galena (white-low relief). × 85.

mates were made for the central and marginal parts. These beds were carefully selected for their lack of replacement and crystallization textures so that they would be as near as possible to their original state.

The measurements for roundness and sphericity were made in only two planes. *Roundness* (Fig. 4a) was estimated by direct comparisons with Pettijohn's chart (31, p. 59), with the following classes: well rounded (WR), rounded (R), subrounded (SR), subangular (SA) and angular (A). *Sphericity* (Fig. 4b) was measured as the ratio of length to breadth and the classes shown as spherical (S), subspherical (SS), subelongate (SE) and elongate (E) correspond to ratios respectively between 1.0–1.1, 1.1–1.5, 1.5–2.0 and greater than 2.0, to unity. Triangular grains were classified visually as were grains less than 1 micron across. The three classes of *aggregation* (Fig. 4c) isolated (I), subaggregated (SA) and aggregated (A) correspond respectively to isolated pyrite grains, grains in direct contact with not more than two other grains, and grains in contact with more than two other grains.

Estimates of the content of pyrite-I spheres in a particular bed, unaffected

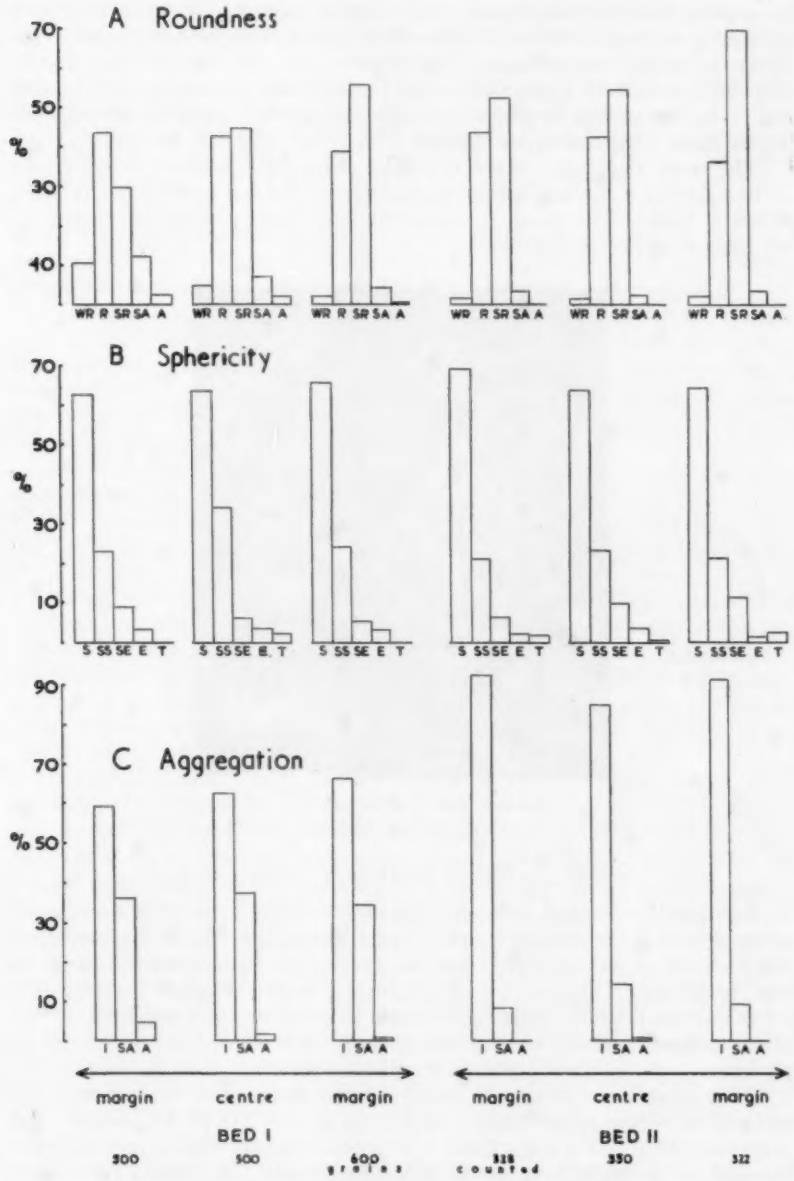


FIG. 4. Pyrite I grains from the Mt. Isa shale.

by recrystallization, were made using a point counter. It was shown that the pyrite commonly accounted for 40–50 percent of the total volume but rarely exceeded this value. None greater than 55 percent was found. Blanchard and Hall (6, p. 15) however record a rare maximum of 75 percent and if in the present study recrystallized specimens were considered, the higher figure might easily be reached.

The most significant factor emerging from the statistical study of the pyrite spheres, is the consistency of the properties found within and between different beds. This point is examined subsequently when the origin of the bedded pyrite is discussed.

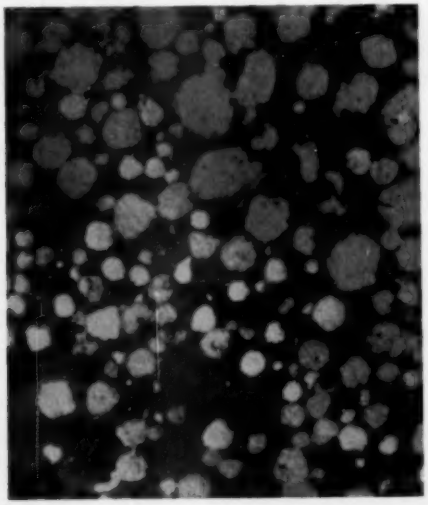


FIG. 5. Pyrite spheres (white) and galena spheres (light gray) in sphalerite (dark gray) with some gangue material (black). × 1,100.

Sulfide Content of the Bedded Pyrite Layers

Pyrite.—No evidence has yet been observed from the Northern Leases of the presence of pyrrhotite with the pyrite, although at Mount Isa Blanchard and Hall (6, p. 15) note that "the fine grained pyrite contains pyrrhotite in solid solution." They also list detailed analysis of the pyrite-I (6, p. 16). In the present study slight differences have been observed between the zones forming the individual pyrite spheres (see below) but no means of analysis e.g. the electron probe, were available for their study at the time.

Other Sulfides.—Spheres of sphalerite and galena have been observed in some of the bedded pyrite layers (30, Fig. 33; 6, Fig. 25; 17, Fig. 66, 70) and Schouten (35, p. 355 & Figs. 2 and 12) records "beds of chalcopyrite spheres" identical with the bedded pyrite from the Mount Isa mine. The galena spheres have only been observed in abundance in remnants of shale-pyrite

layers now enclosed by massive sphalerite (Fig. 5). Sphalerite spheres are relatively common in some pyrite layers away from the main zones of massive sulfides. Schouten (*37*) has presented a strong argument for the spheres being pseudomorphs of the pyrite but it is suggested here that there is a case for their having the same origin as the bedded pyrite spheres. It is hoped to discuss this point more fully in a subsequent paper by the second author.

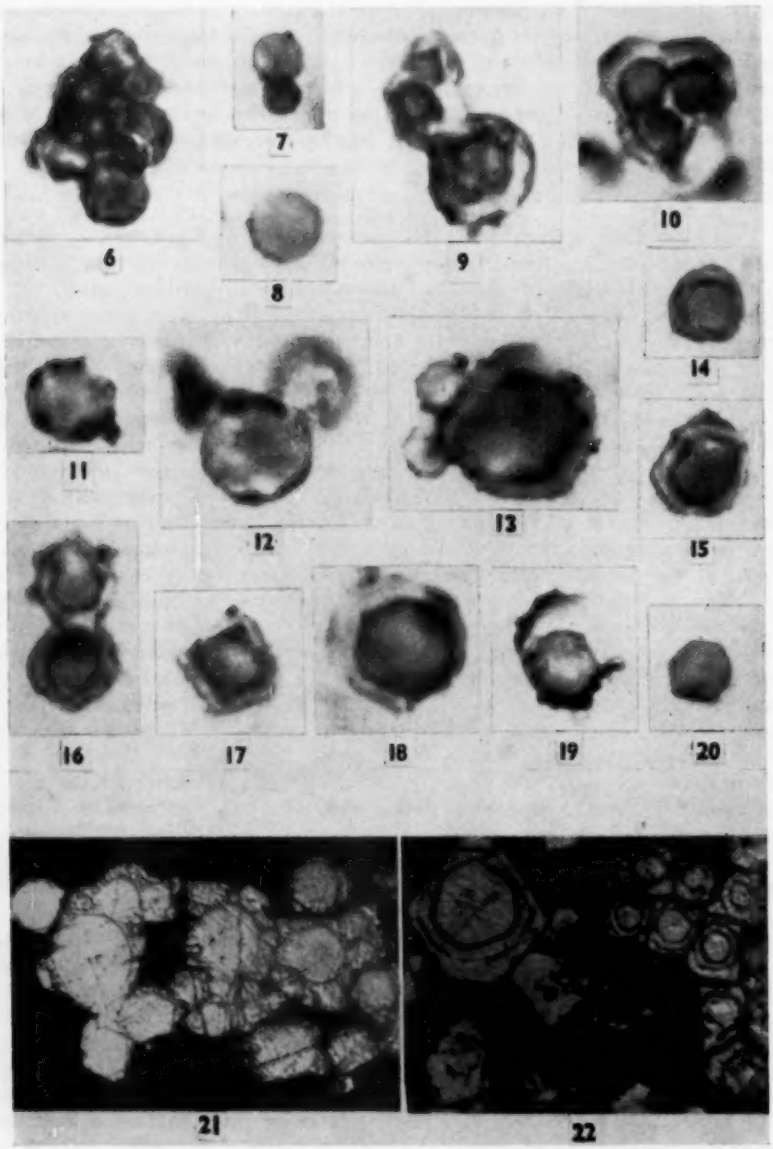
Zoning Structures of the Pyrite-I

In their study of the Mount Isa ores Grondijs and Schouten were the first to note that the pyrite-I spheres were not homogeneous but that "etching with nitric acid shows a marked difference between core and shell" (17, p. 416 & Fig. 62; also see 35, Fig. 24). In the present study, pyrite spheres were generally of a homogeneous appearance prior to etching. An electrolytic etch using 5 percent chromic acid solution gave better results than nitric acid, and features of internal zoning were revealed in many specimens. Some grains remain completely unaffected by the etching process and this is thought to be partially due to imperfections of the etching technique.

Most of the pyrite spheres and tiny crystals in massive sulfide zones show a clear, homogeneous, spherical core (Fig. 21), yellowish white in reflected light and free from inclusions. Separated from the core by a dark line is the enclosing outer shell which tends to be rather ragged and formless. It may be noted that in the specimen figured, heavy etching has revealed in the outer zone a surface texture reminiscent of the framboidal texture well known in other deposits. In areas of recrystallization and/or massive sulfide, the outer zone usually completes a subhedral to euhedral crystal shape for the whole grain. This outer zone tends to be yellowish brown in color and generally contains fine dust-like inclusions; further, it gives the appearance of being more readily attacked by acid, a fact in accordance with its greater impurity.

In some sections, more heavily etched, (Fig. 22) many grains show an additional circular line, thus giving two, of which the inner is thicker and darker. Of the three concentric zones of pyrite so delineated, the outer two contain inclusions and are more strongly attacked by acid than the central zone which is of clear pyrite. In these characteristics, then, the central zone of the three-zone grain resembles that of the two-zone grain, but the outer zone of the latter resembles the outer zone of the three-zone grain. The central zone of the three-zone grain, in about 70 percent of 650 instances measured, showed no relation to subhedral or euhedral crystal shape, and in the characteristics of shape the majority showed perfect sphericity and were well-rounded to rounded, with a size mode of 2 to 3 microns. The measured properties of the central zone are markedly similar to those of the whole pyrite spheres quoted in Figs. 4 and 25. It is not possible to agree with Grondijs and Schouten (17, p. 416) "that generally a grain is built up around a well-crystallized core."

Another interesting arrangement elucidated by etching is the type of aggregation of pyrite spheres, such as in Fig. 2. What appears to be a



FIGS. 6–20. Micro-fossils from solution of pyrite spheres. Transmitted light, oil immersion, all approx. × 2,500.

homogeneous, rather formless grain, becomes a mass of small spheres cemented into a group by coalescence of the pyrite which forms the outer shell of the sphere. No cases of coalescence of the central zones of the pyrite have been observed so far.

Some of the larger spheres show a series of faint concentric rings within the core (Fig. 23).

FIG. 23. Etched pyrite grains showing faint concentric rings. In oil, × 2,500.

Isolation of the Micro-Organisms

Preparation of the Pyrite Sulfide Concentrate.—The first stage in the isolation of the micro-organisms is the preparation of a concentrated sample of the sulfide. This is done by grinding a clean sample of the rock in agate and steel mortars until it passes completely through a sieve of 200 micron size mesh. The powder is then centrifuged in bromoform in accordance with the standard procedure for separation of heavy minerals. Keeping the heavy residue in the centrifuge tube, successive washings with alcohol remove the bromoform, and the specimen is finally washed in distilled water. Microscopic examination of a droplet of the resultant product usually shows some small quantities of gangue material such as quartz, clay mineral, or

FIG. 21. Pyrite grains in carbonate (black). Electrolytic etching in 5% chromic acid shows the double zone arrangement with some coalescence of the outer (secondary growth) zone between grains. In oil × 1,350.

FIG. 22. Pyrite grains with subhedral outlines in carbonate (black). Electrolytic etching in 5% chromic acid shows the triple zoning and double core phenomenon. × 1,250.

carbonate, mostly adhering to sulfide in larger composite grains that have escaped the fullest effects of grinding. To clear such material, hydrofluoric acid is added to the sample, which is stood on a hot water bath for at least three days with occasional agitation. In some instances the acid produced effervescence with release of hydrogen sulfide, probably due to decomposition of galena.

After this stage in all preparations mounts were made for microscopic examination in transmitted light, and some samples from shale containing pyrite-I were dried and mounted in cold setting plastic for polishing as an additional check that unwanted minerals were, in fact, removed. The polished samples showed over 95 percent of sulfide mineral, mainly pyrite with a little sphalerite, chalcopyrite, and pyrrhotite. The isolated pyrite grains when etched with nitric acid showed the internal zoning described in the previous section.

In addition, each sample of the material for treatment as below was examined for the presence of free organic material and in no case was any to be seen.

Oxidation of the Pyrite Concentrate.—The second stage, revealing the micro-fossils from the pyrite grains, is carried out by controlled oxidation with concentrated nitric acid. The timing and temperature necessary vary from sample to sample and must be determined by experimentation, for while the reagent successfully dissolves the sulfide it also attacks the organic material so exposed. After a suitable time interval the acid is diluted and gradually removed by washing and centrifuging to leave a concentration of any residual material. This can be drawn off and mounted in glycerine jelly. Microscopic examination may reveal large numbers of very small translucent bodies comparable in size with the original spheres or pyrite. These bodies are later described in detail and shown to be organic. Rocks whose pyrite yielded such micro-organisms always contained bedded pyrite-I. No micro-organisms were obtained by solution of concentrate prepared from massive and vein-type pyrite of post pyrite-I paragenetic age.

Visual and Other Checks on Results.—In both the above stages it is necessary to exclude all contamination from other rock dust and atmospheric dust, both inorganic and organic. Freshly distilled water only was used for washing the preparations.

Various checks against contamination were made, using slides of material made at all stages of the preparations. Both the preparations yielding micro-organisms and those showing negative results were repeated, with complete consistency of conclusions. Further, certain beds that do not contain pyrite-I or appreciable quantities of other sulfides were examined but no organisms were obtained from the resulting very small pyrite yield.

The most elaborate method of independently establishing the results claimed lies in actual observation of individual grains of pyrite dissolving. This method, developed by one of the authors (26, p. 432), involves the use of a specially devised cell (Fig. 24) that allows continuous microscopic observation of the reaction in nitric acid under high power oil immersion objectives without harm to the microscope or discomfort to the observer. In

the present case, a 2 mm objective was used. A few drops of the acid are added to the slide and the open space covered. The reaction starts as soon as the acid spreads across the pyrite grains and often is quite violent in appearance due to the effects of surface tension and occasional effervescence. After a few minutes the equatorial margin of the spherical dark grain becomes somewhat translucent, while a dark core remains until in all specimens successfully watched it too disappeared leaving behind a variety of forms

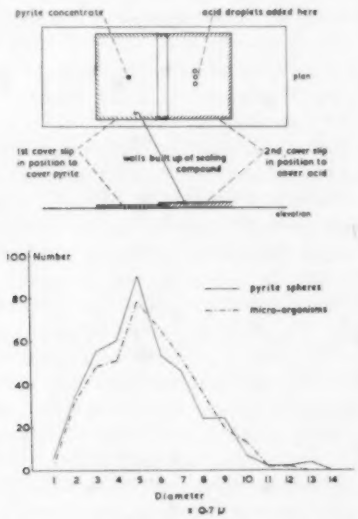


FIG. 24 (upper). Construction of cell on a 3″ × 1″ microscope slide for observation of solution of pyrite at high magnification. Vertical scale of elevation exaggerated.

FIG. 25 (lower). Size range of micro-fossils prepared from part of a sample of pyrite concentrate and size range of pyrite grains in another part of the same sample.

resembling those in Figures 6 to 20. At the magnification used, free movement of the specimens means the method is more suited for individual observation than for the camera.

Description of the Micro-Organisms

It is proposed to leave systematic treatment of the fossil micro-organisms to a subsequent palaeontological paper where new forms of various geological ages but of a similar mode of occurrence may all be considered together.

The micro-organisms from the Mount Isa rocks have been found in great numbers and have a smooth surface with no marking. They are generally rounded or slightly polygonal and they range in size from 1 to 12 microns. The size distribution of a typical sample is given in Figure 25,

together with that of a sample of the concentrate of pyrite grains from which the organisms were obtained. The values at 1 micron and less cannot be regarded as reliable and undoubtedly many bodies in this range could not be distinguished. Dominant numbers are in the 2 to 4 micron size range. The bodies are mainly isolated (Figs. 8, 14) but also occur in clusters (Fig. 6). While some of these may be the result of fortuitous aggregation, others seem to be in an original state of union. Figures 9, 10 and 16 show the component parts having no intervening partition but rather being continuously enclosed in a common outer tissue developed at the contacts.

A few bodies show some trace of adhering material of a form that suggests some original thread-like attachment to other material. No example seen, however, is convincing (Fig. 11).

The micro-organisms are a pale, almost transparent, gray to a barely translucent darker shade. Some of the paler specimens are free from any internal structure or contents (Figs. 7, 8, 12) and consist of a hollow sac that is liable to be broken open, perhaps during the oxidation process. Clearly other pale specimens show an internal structure of a rather darker shade of gray (Fig. 14). This may be polygonal and generally, but not always, the external shape of the body tends to follow this inner form rather than be circular in outline (Fig. 15). The extreme case of a square has occasionally been noted (Fig. 17). The inner structure appears to be a second layer of tissue for it can be seen to remain intact when the outer sac has been torn away (Fig. 19). Figure 20 shows what is probably such an inner body from which the whole outer sac has been lost. The inner bodies may occur separately within small "buds" from a larger body, one to each bud, whereas this larger body has a large central structure (Fig. 9). In other cases, however, small bodies that might be buds are empty (Fig. 13). It is difficult to decide on the proportions of simple to double-layered bodies, since the distinction can only be made in specimens sufficiently clear to be translucent without having been taken to ultimate destruction in the oxidation process. In the clear bodies about half have the inner structure.

The micro-fossils are composed of non-birefringent material which generally resembles that of micro-organisms of more recent geological times, except in a tendency for a patchy dark appearance (Fig. 12), resembling the effects of carbonization. Intense heating on a microscope slide, of a dried out droplet of a suspension containing the bodies, initially causes charring followed by the disappearance of the bodies. These characters, and the absence of any mineral characteristics, together with the tendency towards roundness and "budding," leave no doubt that the bodies are indeed fossil organisms. The gray but carbonized appearance after oxidation is particularly characteristic of a great geological age, or survival of at least the early stages of metamorphic processes. No attempt therefore has been made to have chemical analysis made of any of the minute bulk quantities of material prepared for these studies.

Although small fossil micro-organisms, thought to be sporomorphs, are now known from Proterozoic rocks, particularly from the efforts of Russian

workers, no records of forms such as described in this paper have been seen in the literature.

Sulfur Isotopes

Since the above observations were completed, confirmatory isotopic analyses kindly made by Professor Jensen of the Department of Geology, Yale University, show that there is a relatively broad spread in the S^{32}/S^{34} ratio, both for pyrite-I and for sulfides occurring later in the paragenetic sequence. Four samples of bedded pyrite-I yielded ratios between 21.77 and 21.97 with an average value of 21.88; eleven post-pyrite-I sulfides, mostly pyrite-II and recrystallized pyrite-I, gave an average ratio of 22.05 with a spread between 21.77 and 22.16. Jensen (20) has recently discussed the spread of such ratios in relation to the origin of sulfides and he has also stated (personal communication) that the relatively broad spread found at the Northern Leases is certainly suggestive of a biogenic origin rather than a magmatic hydrothermal origin for the sulfur. These conclusions support those reached in the present study and are discussed below. Further analyses are being made by Professor Jensen to determine the extent of this spread.

DISCUSSION

Pyrite-I Grain Zoning and the Micro-Organisms

In the preceding section it has been established that fossil micro-organisms are in some way intimately enclosed in grains of pyrite-I. Before discussing how this association may have arisen it is necessary to note the precise morphological relationship between the two.

The grains show two possible structures, generally surrounded by a zone of secondary pyrite. There may be a simple homogeneous sphere or a two-zoned sphere. The inner boundary of the two-zone sphere and the boundary with the secondary pyrite of both forms, are displayed in etched polished specimens by distinct dark lines. Significantly the micro-fossils show two forms, similar in size and shape and, when the double structure is present in the micro-fossils (as in the mineral grains) the inner material is thicker and darker. The dark lines in the mineral (Fig. 22) resemble those figured by Schouten (35, Fig. 24). He described from galena grains (35, p. 352, 355) "an extremely thin rim of graphite or bitumen" of thickness 0.002 mm to 0.0005 mm. This is recorded as being found only around those galena grains that originated with replacement of pyrite spheres. They are not explicitly recorded as in or around pyrite grains except in the instance of Schouten's Figures 18 and 19 (35; & p. 359) where the implied graphite black rim is almost certainly the line marking the difference in polishing relief between hard pyrite and soft galena.

Schouten did not draw the inference, made here by analogy between the dark lines revealed in the grains and the known structure of the micro-organisms, that the dark lines mark the position of the micro-fossil walls. Either they are visible due to the "graphite or bituminous" composition of these walls, or simply the dark line is a mineralogical relief effect between

the two slightly different pyrite zones whose interface, however, is itself positioned by the invisible organic wall.

Clearly then, the outermost zone, when secondary pyrite occurs, is external to the outer fossil skin, but the core pyrite must lie within this skin, whose thinness and translucency would render it normally invisible except in etched polished sections. Most grains show at least some trace of the formation of an outermost zone of secondary pyrite.

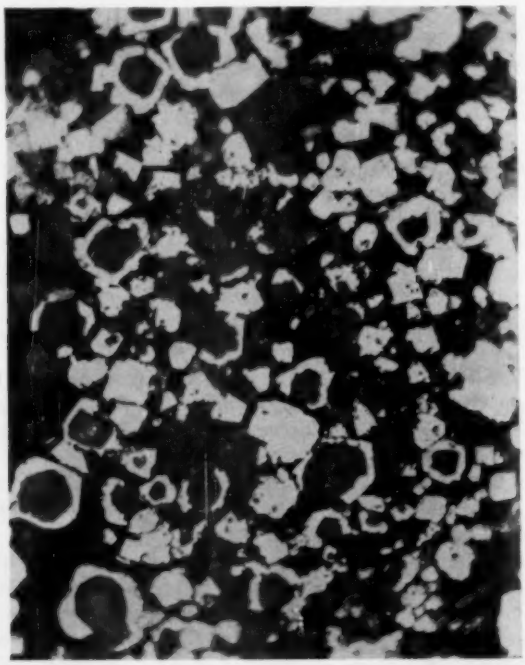


FIG. 26. Pyrite-I grains (white) partially replaced by sphalerite (gray) forming atoll structures. × 800.

Relation of Grain Zoning to Atoll Structures

It has been shown that variations within a pyrite grain as revealed by etching are related to the presence of a micro-organism and it is suggested that they play a significant part in the formation of some atoll structures. The latter (Fig. 26) tend to develop where pyrite-I spheres occur immersed in massive lead and zinc sulfides and they have already been adequately described and figured (35, 37). Briefly, atoll structures consist of pyrite-I grains with a central zone of sphalerite or galena or both in concentric rings. The types observed in the Northern Leases ore show no notable differences from those described from Mount Isa.

Electrolytic etching of specimens containing pyrite-I grains and grains with atoll structures was carried out to determine whether any relation could be observed between the pyritic core zones and the atoll cores formed by the metasomes. Etching showed that unreplaced pyrite-I grains almost invariably exhibited the core zoning. In a few cases these cores are matched in size by adjacent atoll cores but generally the latter are larger.

The atoll structures indicate a differential resistance to replacement within the pyrite grains. Etching has shown that the zones within the latter are slightly different in composition, with the outer shells being more impure (containing inclusions) and more susceptible to acid attack than the cores. Chemical principles dictate that a more impure form is more reactive and this is in accordance with the observations on the outer shell. In contrast, this is directly opposite to the relative rates of replacement indicated by the atoll structures. This reversal is probably governed by the enclosed microfossil since the pyrite within the skin of the fossil is most susceptible to replacement.

"Syngenetic" Origin of the Bedded Pyrite

Grondijs and Schouten (17) were the first workers to make a detailed polished section study of the Mount Isa ore, from which they concluded that the deposit was formed by epigenetic processes. However they "reluctantly" admitted (p. 447) the possibility of a syngenetic origin for the bedded pyrite-I because their observations failed to contradict the theory. The origin of this pyrite has remained conjectural ever since.

Blanchard and Hall (5, p. 1048–9) provided field evidence in favor of an epigenetic origin; firstly, that pyrite-I occurred only within shear zones in the shales and did not occur outside these zones; and secondly, that the pyrite-I formed a general aureole around the main lead-zinc mineralization and did not extend far beyond this. These assertions, while quite justified on the evidence available at the time, are refuted by the work summarized in this paper. It has been shown that the pyrite-I may persist over the greater part (26 miles) of the outcrop length of the Mount Isa Shale (approx. 30 miles). Further, the reported occurrences are all in roughly the same stratigraphic horizons, and these are not sheared throughout their length. This reinterpretation of Blanchard and Hall's field criteria alone constitutes substantial evidence for an origin more closely associated with that of the host shales.

Further evidence is seen in the manner in which pyritic beds persist laterally through small scale contortions and displacements. In addition, slivers of pyritic shale seemingly "floating" in massive sulfides (Fig. 3) are interpreted as fragments of shale broken away by, and incorporated into, mobile plastic sulfides prior to recrystallization.

Recent discussion of the Mount Isa deposit confirms that the pyrite-I is probably syngenetic. Murray, Carter S. R., & Hall (27, p. 955) state that the pyrite-I "is commonly accepted now to be syngenetic" and S. R. Carter in a personal communication reaffirms that this conclusion is based on field evidence and associations. Raggatt (32, p. 62–3) has gone a step closer to

detailing the genetic processes by speaking of "the shale characterized by bedded (diagenetic ?) fine-grained pyrite."

Further evidence for a syngenetic or early diagenetic origin is mentioned below in conjunction with the role of the micro-organisms. Comparison with more recent pyritic shales, in which the pyrite undoubtedly occurred in the original sediment, suggests that the pyrite-I of the Mount Isa Shale was formed by similar processes. In the virtually unaltered shale where replacement and recrystallization textures are absent, many characters of the rock are closely comparable with features of shales, for instance, of late Palaeozoic and early Mesozoic age.

Indirect evidence for syngenesis exists in the shape of the grains. The consistency of size and shape characteristics in different beds and the dearth of euhedral and subhedral forms suggests some genetic control other than normal epigenetic crystallization processes.

Environment and Role of the Micro-Organisms

In the only published study of this nature (26) it was suggested that the role of micro-organisms isolated from the pyrite might include the production of hydrogen sulfide, with resulting precipitation of iron sulfide in and around the organism. Two factors led to this hypothesis. The first was the intimate and apparently unique relationship between the micro-organisms and the pyrite. In various rocks containing even much well preserved organic material, none of the particular micro-organisms in question could be found free from pyrite. Secondly much detail could be inferred from the environment of deposition of the rocks that were bituminous shales and bituminous limestones of Carboniferous age. In the Mount Isa material no unpyritized occurrences of the micro-organisms could be found but clearly little can be stated about the conditions of deposition of the rocks.

It is therefore by analogy, based on the similar mode of occurrence of the micro-organisms, that their role in the production of iron sulfide is suggested and no refinements of the theory can at present be given. Attempts at this however, for late Palaeozoic and early Mesozoic rocks are being made and the environment in which certain micro-fossils are found associated with spherical pyrite is becoming clearer. The greatest abundance of pyrite spheres occurs in beds that originated as sapropelic muds, characteristically rich in soft organic material such as spores, algae, and remains of much more unrecognizable detritus. Furthermore, where this material is abundant the finest stratification is generally preserved, indicating not only a lack of any extensive water circulation but also, perhaps consequently, a lack of any disturbance particularly by burrowing animals. In extreme cases fossil remains of ordinary bottom-dwelling animals may be absent, although those of near-surface forms such as cephalopods, crustaceans, fish and floating algae may be common. These associations clearly indicate a foul bottomed, anaerobic environment with toxic conditions in the lower waters or at some specific level in the mud, tending to exclude the host of bottom living or burrowing scavengers which would normally allow little but skeletal material to remain.

In these conditions the role of the "pyrite micro-organisms" might be explained by theories other than the one noted. Those imputing a purely passive role would invoke some unexplained catalytic actions to induce reaction between iron and sulfide ions, or provide that the chemical composition of the organisms was such as, on decay, to yield sulfide for such precipitation. Its quantity could hardly be enough for the volume of pyrite produced here. In an active role the organisms could serve to concentrate iron and sulfide to a level, lacking outside, at which reaction could take place.

Although these organisms are not necessarily regarded as bacteria, certainly the formation of hydrogen sulfide by bacterial action is an established fact. Rubenchik (33) quotes other workers as saying that "99.4–99.6 per cent of the total amount of H_2S in the Black Sea was formed from sulfates in the sea water as a result of the activity of sulfate-reducing bacteria." Ivanov (18, p. 544) in discussing the role of bacteria in the formation of sulfur deposits, says that they "play a significant role at both stages of the cycle-$SO_4^=$ to H_2S to S." Bastin (4, p. 774) was perhaps one of the first geologic workers to draw attention to the presence of H_2S in waters associated with petroleum reservoirs, and showed that it was produced from sulfates by the action of anaerobic bacteria. One of the criticisms of the theory as presented in 1958 (26, p. 438) was "that a volume of gas over 1000 times as great as the volume of the organism would be required" but Rubenchik (33) notes certain cultures producing a total of 2400 mgms. H_2S per litre and Ivanov (19) quotes a bacterial production of 2 mgms. of H_2S per litre of water per day, under favorable conditions.

If the micro-organisms found in the Mt. Isa Shale were producers of hydrogen sulfide, they could actively cause the precipitation of ferrous sulfide from iron in solution, "because iron is the principle acceptor of the H_2S formed" (2, p. 243). Many examples of this process exist in sediments forming today without particularly high iron concentrations being present in solution. As high concentrations of molecular H_2S are toxic to sulfate-reducing bacteria (33) fixation of the H_2S as FeS would allow such a colony to survive.

The S^{32}/S^{34} isotopic ratios obtained for pyrite-I (21.77–21.97) have some interesting correlations. They are in accord with values obtained for sedimentary sulfides (range 21.3 to 23.3) and they also conform to ratios obtained from sulfur in sea-water sulfates whose range is 21.7–21.9 (38). The Northern Leases sulfur ratios are, therefore, quite reasonable for hydrogen sulfide of biogenic origin (range 22.05 to 22.75) derived from sea-water sulfates. Isotopic fractionation according to the following isotopic exchange reaction indicates that the resulting H_2S derived from the

$$S^{32}O_4^= + H_2S^{34} \rightleftharpoons S^{34}O_4^= + H_2S^{32}$$

reduction of $SO_4^=$ should be enriched in the lighter isotope. It has, furthermore, been shown by Jensen (20) that H_2S of biogenic origin is not enriched in the lighter isotope by a constant amount but the anaerobes produce H_2S with a considerable variation in the S^{32}/S^{34} ratio. This has also been noted by Kaplan, et al. (21). The significant spread in S^{32}/S^{34} ratios of the

Northern Leases sulfur is, therefore, quite suggestive of sulfur derived from H_2S of biogenic origin.

Few records of organisms depositing iron sulfide within their bodies have been found although this phenomenon too is undoubtedly established. Rubenchik (33) noted granules of black FeS within the cells of the only significant sulfate-reducing bacteria genus, *Sporovibrio*, and Love (26, p. 430) has already mentioned records of *Actinomyces* and bacteria with internal deposits of black sulfide. The dearth of such records may in fact be due to the organisms thus losing their normal appearance.

The nature of the original sulfide deposited is uncertain. It is probably ferrous sulfide in an amorphous form and several workers have already commented about it as follows. Rubenchik (33) says that "the H_2S formed by *Sporovibrio* is converted into iron sulfide and the latter is changed within the cells of the indicated bacilli, at first possibly into melnikovite, and then into pyrite." Lepp (25, p. 528) has prepared synthetic melnikovite by the action of hydrogen sulfide on a ferrous solution at room temperature and he describes the product as a sooty black, cryptocrystalline, magnetic iron sulfide hydrate. Further, he found that partial conversion to pyrite occurred when the synthetic melnikovite was held at approximately 75°C. under a pressure of 14,000 pounds per square inch for only one hour. Emery and Rittenberg (14, p. 791) have suggested that a slime of hydrotroilite is first formed under the conditions postulated here, again with later conversion to pyrite. Finally Got'ye (in 33) states that iron sulfide that is in simultaneous contact with free H_2S and free oxygen is converted into pyrite.

Approaching the problem from the opposite direction, Baas Becking and Moore (3) have synthesized most of the common sulfides including FeS by bacterial action under laboratory conditions simulating the natural environment. A possible mechanism for the formation of more complex sulfides may involve processes such as solid diffusion and physicochemical conditions developed during metamorphism (16, Khitarov, in 12).

It is not known whether the "organic" iron sulfide is produced at the surface or at some depth in the subaqueous mud (26, p. 435). If the process takes place at some depth in the subaqueous mud before lithification the sulfide is not strictly contemporaneous with the deposition of the adjacent sedimentary grains and perhaps should be regarded almost as diagenetic. The distinction of whether the sulfide is strictly syngenetic or diagenetic in this sense seems almost irrelevant in the time scale involved in the geological history of the Mt. Isa rocks.

Although the mode of occurrence of the organisms in the Mount Isa rocks, and consequently their suggested role in the near syngenetic production of iron sulfide, parallels those of other rocks studied by Love (26), their appearance is different. The occasional budding of smaller bodies from larger ones however, and the occurrence of inner bodies in many of the sacs (possibly related to reproduction also) are to be found in their presumed counterparts of Paleozoic and Mesozoic age. The exact significance of all these forms, especially in relation to systematic taxonomy, is not yet fully elucidated and will be left to a publication of wider scope in its source material.

Origin of the Massive Sulfides

It is not proposed to discuss in detail the origin of the massive sulfides that crystallized after the pyrite-I, since little relevant information has been added to earlier work (11, 15, 24, 27, 32, 39, 40) and it is proposed to discuss the problem more fully in a later paper by the second author. However, two points are worthy of comment.

Firstly, Blanchard and Hall's statement (6, p. 15) that "the fine grained (pyrite) phase constitutes approximately two thirds of all sulfides eventually deposited in the district" is ripe for elaboration. There is no reason to doubt their statement because extensions to the known volume of sulfides since 1942 seem to be greater for pyrite-I than for the 'younger' sulfides. Thus more than 60 percent of *all* sulfides in the Mt. Isa district appear to have a sedimentary-diagenetic origin. This assessment rather alters the perspective of the controversy about the origin of the Mt. Isa sulfides and it might be interesting to apply this knowledge in the type of genetic analysis suggested by Amstutz (1).

Secondly, the biogenic theory of origin of certain types of ore deposits, perhaps first proposed by Bastin in 1926 (4), warrants reconsideration. From the preceding paragraph it is clear that micro-organisms have been responsible for the accumulation of enormous tonnages of pyrite, and it has been mentioned that bacteria are capable of precipitating most of the common, simple sulfides (3). Clearly, the difficulty in the biogenic theory is the problem of how the economic metals arrived in solution in sufficient quantities to be concentrated by the micro-organisms. Two possibilities come to mind, either the direct weathering of exposed ore-bodies into the sedimentary basin, or submarine volcanic (29) or hydrothermal emanations on the sea floor as proposed for the Rammelsberg deposit (22).

Allowing that the sulfides may be deposited as suggested above, then, after burial and during metamorphism, the mineralized zone could be compared with a "closed" hydrothermal cell. Gill (16) and Khitarov (in 12) have described mechanisms whereby simple sulfides are converted to more complex forms with attendant changes in mineralogy; the physicochemical conditions accompanying this process are similar to those associated with metamorphism (12). The changes (i.e. remobilization) occurring in the proposed 'hydrothermal cell' would presumably result in textures and structures similar to those associated with normal hydrothermal ore deposition, derived from another missing link—the deep seated magma with its mysterious "plumbing." Undoubtedly both mechanisms of ore deposition have occurred during geological time. Fisher has recently critically examined both of these theories applied to the Mt. Isa deposits and found the balance of evidence in favor of the syngenetic-remobilized theory (15).

SUMMARY AND CONCLUSIONS

1. The importance of microspherical grains of pyrite as the first generation of mineralization in the Mount Isa Shale is emphasized.
2. Most of the grains have an outer zone of secondary pyrite.

3. These grains have been shown to incorporate fossilized micro-organisms of a size comparable with that of the grains.

4. The micro-organisms are only found in association with grains of pyrite-I and never in an unpyritized condition.

5. The micro-fossils are described but their systematic taxonomy is left to a later paleontological paper.

6. The fossils appear to be analogous with forms of Paleozoic and Mesozoic age that are characteristic of the environment of deposition of sapropelic black shales.

7. Two forms of structure are found in the micro-organisms, a simple spherical sac and one with an extra internal sac.

8. Etching reveals two types of core within the pyrite grains, around which a zone of secondary pyrite may occur. One type is homogeneous and the other consists of two zones.

9. The interzonal boundaries are marked by dark lines in the etched polished specimens.

10. The structure of the organisms closely resemble the boundaries of the zones of the pyrite spheres in size and shape.

11. It is inferred that the pyrite was deposited in the micro-organisms, probably as an amorphous sulfide, resulting from secretion of hydrogen sulfide by the organism.

12. This amorphous sulfide was syngenetic with deposition of the sediment or occurred at the time of early diagenesis before complete lithification to shale.

13. The apparent ease of replacement of the cores of pyrite-I grains to give atoll structures is probably governed by the micro-fossils.

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SOME ASPECTS OF ARCHEAN STRUCTURE AND MINERALIZATION

A. M. GOODWIN

TABLE OF CONTENTS

	PAGE
Abstract	897
General statement	898
Acknowledgments	898
Michipicoten area	899
Introduction	899
General geology	899
Structure	900
Relation of clastic sediments to volcanics	901
Relation of mineral deposits to volcanics	902
Relation of younger granite to Michipicoten series	905
Summary of conclusions	906
Superior-Timiskaming region	907
Introduction	907
General geology	907
Structural interpretation	912
Folding	912
Faulting	913
Metallogenic relations	913
Distribution and nature	913
Interpretation	913
Concluding statement	914

ABSTRACT

The Michipicoten area of north-central Ontario, one of numerous volcanic-sedimentary segments distributed across the Canadian Shield, represents an Archean composite favorable in composition, structure, size and location for elucidation of certain structural and metallogenic problems. Detailed investigations of Michipicoten rocks have led to the following tentative conclusions: 1) Undulating sectional fold patterns have resulted from the association of east-west primary folds and north-south cross folds; 2) Younger, pre- or syn-tectonic granite of metasomatic derivation, conformably emplaced in the volcanic-sedimentary series, is concentrated along present anticlinal axes; 3) Volcanic extrusives, subvolcanic intrusives, and associated mineral deposits are of common igneous derivation; 4) Syngenetic and epigenetic mineral deposits are distributed along favorable volcanic source horizons, particularly in the vicinity of maximum explosive discharge; 5) Timiskaming-type sedimentary units, which represent contemporaneous erosional products of underlying volcanics, tend to be of local distribution only and are therefore of limited value for purposes of stratigraphic correlation across broad regions.

By way of illustration, the conclusions are applied to a generalized, regional interpretation of Archean segments in the Superior-Timiskaming portion of the Shield, extending specifically from Lake Winnipeg on the west to the Grenville "front" on the east. Major fold axes are located on the basis of established structural plunges, in conjunction with location of regional granite belts. On the basis of predominant mineral deposits, the segments may be grouped into an older iron-gold province, extending from Red Lake on the west to Kirkland Lake on the east, and a younger gold-copper-zinc province extending eastward therefrom to the Grenville "front." It is suggested that mineral provinces reflect contrasting compositions of parental magmas from which mineral deposits and associated volcanics were derived.

Geological data and interpretations are presented in order to stimulate thought and study along similar lines in other portions of the Shield.

GENERAL STATEMENT

THE Canadian Shield contains numerous older Precambrian, or Archean (40, p. 769) segments, mutually isolated by regional masses of younger granite, which resemble in distribution so many volcanic-sedimentary islands scattered in a sea of granite. Volcanic components therein are commonly classed as Keewatin, associated clastic sediments as Timiskaming, and certain persistent belts of quartz-mica schist of uncertain relative age as Coutchiching or Knife Lake; intervening masses of younger granite are generally classed as Algoman. Isolated distribution, lithological similarity, and structural complexity of segments render stratigraphic correlation uncertain; in addition, associated iron, gold and base metal deposits are of uncertain origin. Hence, the segments collectively present many challenging stratigraphic, structural and metallogenic problems.

Archean segments have been studied in varying degrees depending largely on their mineral wealth and location. The Michipicoten segment of north-central Ontario is well suited for detailed study because 1) it contains sufficient variety of volcanics, sediments and associated mineral deposits to afford an insight into stratigraphic and genetic relationships; 2) it is sufficiently large to display a complicated but homogeneous structural pattern; and yet 3) is sufficiently small to have permitted comprehensive investigation on mine and regional scales during a limited period of time. In brief, the Michipicoten segment represents an Archean composite favorable in composition, structure, size, and location for elucidation of certain Archean problems.

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MICHIPICOTEN AREA

Introduction

The Michipicoten area, which is 100 miles long (east–west) and 30 miles wide, lies 150 miles north of Sault Ste. Marie in the northeast corner of the Lake Superior district (Fig. 1). It is surrounded by regional masses

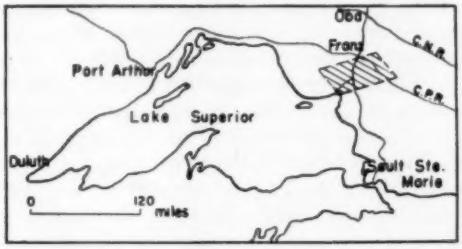


Fig. 1

Index Map Showing Location of Michipicoten Area

FIG. 1. Index map showing location of Michipicoten area.

of granite and is thereby isolated from other Archean segments. The area has been a steady producer of iron ore for many years; several gold properties, now inactive, formerly produced at significant rates.

General Geology

Consolidated rocks of the area comprise older volcanics and sediments of the Michipicoten series, and younger granitic rocks (10). The Michipicoten series is composed of a thick assemblage of mixed flows and pyroclastics together with clastic sediments and banded iron formations. The volcanics, which range from basalts to rhyolite, characteristically exhibit marked variation in lithology and structure over short distances. Andesitic flows of the quiet effusive type predominate. They give way at periodic intervals in the volcanic column to broad, domical, rhyolite-dacite pyroclastic accumulations which range up to 7,000 feet thick in proximity to centres of volcanic discharge. Acid ejectamenta contained therein ranges from well banded, fine grained tuff to coarse, angular breccia containing prominent, hybrid "glowing avalanche" deposits (35, 37). In contrast to andesitic flows,

which signify quiet effusion of long duration, acid pyroclastic accumulations signify brief periods of rapid, violent volcanic expulsion. Numerous diorite-gabbro sills and dikes present in the volcanic column together with small granite, granodiorite and porphyry stocks that occur within, or in close proximity to, acid pyroclastics, appear to represent coeval, sub-volcanic intrusives. Gold and base metal deposits which are closely associated with the intrusive stocks are also interpreted as being of common sub-volcanic, presumably magmatic derivation.

A principal horizon of clastic sediments present in the volcanic column, termed the Dore, ranges from thick, conglomerate-bearing facies in the west to thin, shaly facies in the east. The Dore is conformable to enclosing volcanics for the most part. It appears to represent a product of contemporaneous, subaerial erosion of expanding acid breccia piles. Sedimentation and volcanism occurred simultaneously in different parts of the basin of deposition during Dore time, hence the Dore has volcanic time equivalents.

Horizons of banded iron formation are transgressive from volcanic to sedimentary components of the Michipicoten column. Iron formation of volcanic association, where fully developed, comprises banded chert, pyrite, and carbonate members in descending stratigraphic succession; this type of iron formation typically overlies rhyolite-dacite pyroclastics and underlies andesitic flows; the three members of the iron formation appear to represent chemical precipitates derived by way of hot-springs and fumaroles during a period of chemical activity which followed the highly explosive, acid volcanic phase. Michipicoten iron formations of sedimentary association, on the other hand, are composed of interbanded chert, siliceous magnetite, and jasper—an assemblage typical of many iron formations found elsewhere in Archean volcanic and sedimentary rocks.

Structure

Michipicoten rocks have been extensively folded and faulted but not sheared on as large a scale as have similar rocks in some Archean segments. Metamorphic rank is generally low (chlorite-biotite subfacies of green schist facies). As a result, primary and secondary structures are well preserved. Stratigraphic tops are indicated by pillow structures and graded bedding. Dragfolds, alignment of fragments in conglomerate and pyroclastics, as well as bedding-cleavage relations disclose direction and amount of local axial plunge.

The rocks have been folded about east–west trending cylindroidal axes which have in turn been cross-folded about northerly trending axes. Three main east–west trending primary folds—a central anticline and flanking synclines—cross the map area. In plan view, the axes trace out arcuate patterns striking slightly north of east (Fig. 2). Three northerly trending cross folds give to the primary folds undulating patterns in longitudinal section. Since cross-folds are generally inclines or overturned to the west, primary fold axes generally plunge gently east and steeply west (Fig. 2).

Prominent northerly striking vertical faults with left-hand, horizontal

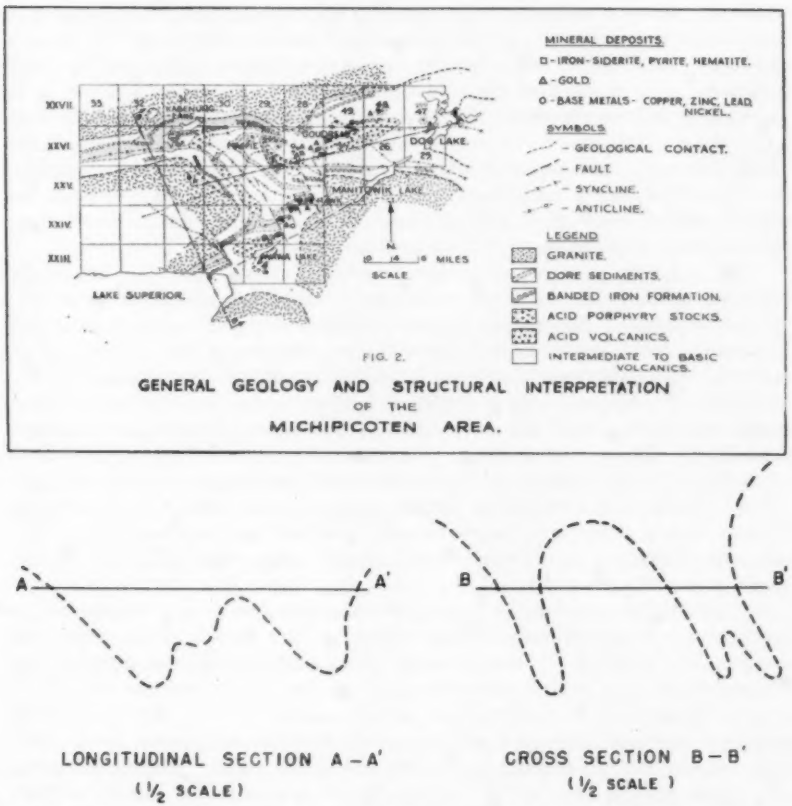


FIG. 2.

GENERAL GEOLOGY AND STRUCTURAL INTERPRETATION OF THE MICHIPICOTEN AREA.

FIG. 2. General geology and structural interpretation of the Michipicoten area.

components of displacement ranging up to 3 miles have sliced the area into large, irregular blocks. A second fault set of moderate thrust displacement has a general northeast strike and southeast dip.

Relation of Clastic Sediments to Volcanics

The Dore group, the main clastic horizon in the Michipicoten series, is composed of thick, conglomerate-bearing, graywacke-argillite zones to the west, and thin, shaly zones to the east. Graywacke lenses and bands with shaly partings range up to 12 inches thick and 100 feet long; sorting on the whole is poor, although graded bedding is locally abundant. The relations indicate rapid accumulation of fine to medium grained clastic debris in moderately deep water. Dark gray, delicately laminated argillite appears to have formed in deeper water by slow precipitation of fine grained clastic

material. Conglomerate lenses of varying dimensions range in distribution from basal to median along the sedimentary bands. Well rounded to subangular, poorly sorted fragments range up to 2 feet in diameter; the large majority are composed of massive to porphyritic felsite and granite, with greenstone and cherty iron formation in lesser proportions. All fragments have their counterparts in underlying portions of the volcanic column. Matrix material is composed of massive to poorly sorted, rudely stratified graywacke or shale. Although evidence of widespread basal erosion or unconformable relation is lacking, local centres of mechanical erosion are present along the flanks of acid pyroclastic columns.

The relations suggest that coarse detritus of volcanic derivation was supplied suddenly and in large quantities to basins of deposition. The terrain during and at the close of periods of explosive volcanic ejection, it may be reasonably inferred, favored rapid, large scale erosion—a terrain of considerable relief, composed of loosely consolidated tuff, breccia and flows; under these conditions, subaerial exposure of enlarging breccia domes, cones, necks and spires would initiate mechanical erosion. The poor sorting, subrounding, rude stratification and great variation in thickness of the Dore all point to rapid erosion and deposition from nearby source areas of high relief. The large size of many boulders suggests that gradients were steep. Coarser debris presumably accumulated in the form of fans and lenses near the source, whereas finer grained ash and dust were more widely distributed as muds and impure sands.

Granite detritus contained in the Dore has been traditionally considered to imply the presence of an older, pre-Dore granite terrain from which the detritus was derived. It seems more likely that the granite detritus was derived from near surface intrusive equivalents of the extrusive acid volcanics. Rapid erosion during Dore time of acid volcanic columns and cones may be reasonably inferred to have exposed near-surface granite feeders and plugs which thereupon contributed detritus to the Dore. The development of granitic texture at relatively shallow depth in a high isothermal volcanic region is a prerequisite to this concept. However, in a region of intense volcanic activity, isothermal gradient would likely be high and granite apophyses would be expected to have typical granitic textures even at relatively shallow depths.

In summary, Dore sediments appear to represent an erosional response to a specific volcanic action—in this case, subaerial exposure of rapidly accumulating acid breccia piles. For this reason, volcanic sediments of this type reflect local conditions and are of limited value for purposes of stratigraphic correlation across broad regions. That is to say, they are unreliable marker horizons beyond the limited confines of a specific Archean segment.

Relation of Mineral Deposits to Volcanics

Iron, gold and base metal deposits occur within, or immediately adjacent to, acid pyroclastic horizons, particularly near centres of maximum volcanic

discharge. Siderite-pyrite deposits, on the one hand, occur within portions of banded iron formations that overlie acid extrusives; gold and base metal deposits, on the other hand, occur marginal to, or within, nearby porphyry intrusive stocks. General geological relationships suggest that acid extrusives, porphyry intrusives, and associated mineral deposits are all of coeval, sub-volcanic derivation.

Large, elongated, domical masses of acid extrusives ranging up to 8,000 feet thick and 20 miles long occur near Wawa lake in the south, Magpie in the centre and Goudreau in the east (Fig. 2). Individual accumulations are composed of rhyolite-dacite tuff-breccia-flow intercalations; they clearly represent centres of violent, explosive, volcanic activity.

In Michipicoten south, from west to east (Fig. 2), the Helen, Eleanor, Lucy, Ruth, Josephine, and Bartlett siderite deposits (24) represent faulted segments of a once continuous iron formation which overlies acid volcanics. In Michipicoten center (Twp. 29, R. 26), the former Magpie mine was located in a siderite lens associated with acid extrusives (6, p. 105–112). Similarly, near Goudreau in Michipicoten east, the Rand, Morrison, Bear, Nichols and McPhail pyrite deposits are contained in a single folded iron formation which overlies acid extrusives. The siderite-pyrite deposits are most reasonably interpreted as being largely of syngenetic origin (11).

Porphyry intrusive stocks, which lie within, or marginal to, acid volcanic accumulations, are characterized by 1) porphyritic cores, 2) felsitic margins, and 3) negligible contact metamorphic effects on adjacent volcanics. They are reasonably interpreted as representing ancient necks, feeder columns and sub-volcanic, high-level magma pockets that were emplaced during the general period of active volcanic discharge.

The Wawa stock, an oval mass some 4 miles long and 2 miles wide which is situated south of Wawa lake, is composed largely of quartz porphyry ranging in texture from medium grained in the center, through finer grained, more porphyritic phases, to felsitic margins (6, p. 125). Gold-bearing, quartz-carbonate veins occupy fractures in the volcanic schist around the margin of the intrusive as well as in the intrusive mass itself. As described by Frohberg (p. 51–73), the gold veins of the area generally consist of a succession of quartz-carbonate bodies that show more or less distinct lenticular form. Their width ranges from a few inches up to 5 feet; their horizontal extent seldom exceeds 100 feet. The gold-bearing quartz occurs along shear zones either in the form of short stringers or in larger lenses. Quartz is generally the main constituent; calcite and ankerite are present in lesser amounts; tourmaline, hornblende, arsenopyrite, pyrrhotite, cubanite pyrite, chalcopyrite, sphalerite, and galena are rarer constituents. Gold occurs both in the native state and in association with the sulfides. Examples of former producers in the Wawa area are the Minto, Parkhill, and Darwin mines.

To the east, between Wawa lake and Hawk Junction, several small gold-bearing quartz veins have been located within small porphyry bodies (5, p. 18). Galena-sphalerite-bearing quartz zones are present in acid pyroclastics 1 mile north of Wawa lake on the former Mammoth Metals property

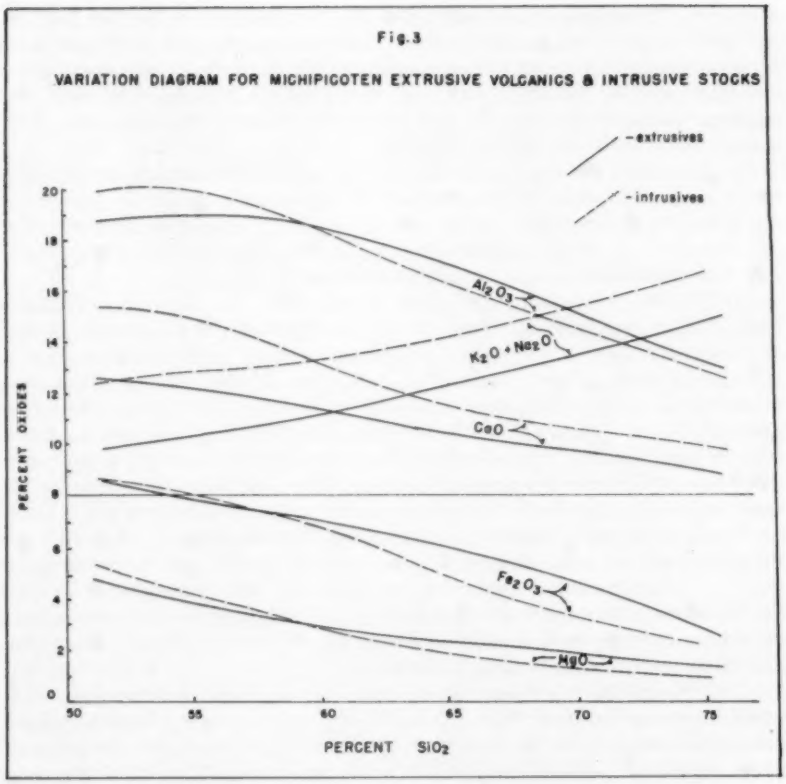


FIG. 3. Variation diagram for Michipicoten extrusive volcanics and intrusive stocks.

(22, p. 41). In addition, chalcopyrite-pyrrhotite disseminations occur in peridotite on the Lakemount property in the vicinity of Sunrise lake in Twp. 28, R. 24 (23, p. 119–121).

In the Magpie area to the north (Twp. 28, R. 26), the Gutcher stock lies at the northeast margin of an acid breccia mass (Fig. 2). The stock forms an oval mass roughly 6,000 feet in diameter composed of light gray, porphyritic to coarse-grained granite with felsitic margins. Surrounding volcanics are not recrystallized to a noticeable extent (6, p. 35). Quartz-carbonate veins which contain free gold, pyrite, pyrrhotite, chalcopyrite, and sphalerite occupy fractures at the margins of the stock as well as in adjoining volcanics. Examples of specific mineral deposits are the Barnes, Amherst, Brighton, Porter-Dormier, Banville-Page, and Brandt properties (9, p. 69–73). To the east of the Gutcher stock, several smaller granodiorite

stocks are situated near the north margin of the Goudreau acid breccia mass (Twps. 28 and 27, R. 26, and Twp. 49). The Cline lake stock, the larger of these intrusives, which is roughly 4,000 feet in diameter, contains both porphyritic and massive phases (2, p. 35–36); it contains gold-bearing quartz-carbonate veins (2, p. 38–40) similar in size and composition to those present in the Wawa and Gutcher stocks.

A variation diagram of Michipicoten extrusive and intrusive rocks (Fig. 3), indicates the chemical similarity of the two groups of rocks; it supports the suggestion that both groups belong to the same magmatic provenance. Lower CaO and alkalies in the extrusives reflects leaching and removal of these constituents by carbon dioxide, which is consistently present in the extrusives but generally absent in the intrusives.

The close spatial affinity and chemical similarity of acid extrusives and porphyry stocks, together with absence of significant contact metamorphic effects, support the inference that extrusives and intrusives are of common, sub-volcanic, presumably magmatic, derivation, and that the porphyry stocks with associated mineral zones represent sub-volcanic emplacements formed during periods of high geothermal gradient that accompanied the volcanic activity. The setting envisaged is similar to that described by Turneaure (36) in central Bolivia where tin-silver ore deposits are closely related to volcanic extrusives and quartz porphyry intrusives of Tertiary age. Turneaure concludes that the intrusive igneous rocks of the region are of shallow-seated character, that the ore deposits likewise were formed relatively close to the original surface, and that the volcanics, intrusives and ore deposits all probably owe their origin to the differentiation of the same parental magmas in depth (p. 602).

Relation of Younger Granite to Michipicoten Series

Broad belts of younger granite with gneissic margins surround Michipicoten rocks on all sides. Transition zones, in which chlorite-quartz-biotite assemblages typical of the unaltered volcanics grade through dense, occasionally porphyritic amphibole schist with increasing proportion of quartz veins, aplites, pegmatite dikes and migmatite layers, to granite gneiss with relict patches of metamorphosed schist, range in width up to 6,000 feet. A striking feature of the relationship is that foliation in bordering granites is everywhere conformable in attitude to primary flow and bedding features in adjoining host rocks, regardless of whether steeply dipping as occurs at the north and south borders of the area, or gently dipping as occurs at the west border (Fig. 2). (Many field workers in north-western Ontario have noted the parallelism of Keewatin-Timiskaming belts and younger granites. (32, 1932; 25; 13). Thus, notwithstanding cross-cutting relationships in detail, younger granites occupy a conformable stratigraphic position towards the base of the older volcanic-sedimentary series. Expressed in terms of present structural distribution, granite is more plentifully exposed along anticlinal axes than along synclinal axes.

The close structural concordance and gradational relationships of foliated granite and volcanic-sedimentary host rocks suggest pre- or syn-tectonic, metasomatic emplacement of the granite. The fact that the main mass of volcanic-sedimentary rocks is well within the greenschist facies of metamorphic rank indicates that "granitization" occurred under relatively low temperature-pressure conditions (epizonal), such as prevail at shallow depths in the earth's crust.

Close structural concordance of volcanic-sediments and younger granite suggests some common feature linking both accumulation of the volcanic-sedimentary series and emplacement of younger granite. A common geothermal heritage constitutes a possible link. According to this hypothesis, geothermal elements operative in Michipicoten time exerted fundamental tectonic-volcanic control during accumulation of the volcanic-sedimentary series; this was followed, in response to increased thermal gradient, by emplacement of metasomatic granite. A fundamental geothermal rhythm is suggested, with the older volcanic-sedimentary series being the product of moderate thermal activity, and granitization and tectonic disturbance being the product of a more intense thermal phase. Thermal rhythms of this type, repeated intermittently across broad regions and over long time intervals, may have produced Archean segments such as are present in the Michipicoten area and adjacent portions of the Shield.

Summary of Conclusions

Five tentative conclusions have been drawn from detailed investigation of the Michipicoten area:

1. The structural association of east-west primary folds and north-south cross folds has resulted in undulating fold patterns in longitudinal and cross-sections.

2. Younger granite, largely of metasomatic origin, is structurally conformable to volcanic-sedimentary host rocks. In terms of present structural distribution, granite is concentrated along anticlinal zones. Thus, the distribution of regional granite belts tends to rectangular patterns, east-west granite belts conforming to primary anticlinal zones, and north-south granite belts to cross anticlinal zones.

3. Volcanic columns composed predominantly of intermediate to basic volcanics contain occasional acid volcanic horizons. Such horizons characteristically comprise acid pyroclastics and flows, intrusive stocks, and associated mineralized zones, all of common, subvolcanic, presumably magmatic derivation.

4. Ore zones associated with acid volcanic horizons occur in the form of syngenetic deposits (Fe-sulfides, carbonates, oxides; possibly Cu-Zn-sulfides), and/or epigenetic fracture fillings or replacements of favorable host rocks (native Au, Cu-Zn-Pb-Ni-sulfides). Since post-emplacement migration of syngenetic deposits to favorable structural sites is possible, mineral

deposits may be 1) primary syngenetic, 2) primary epigenetic, or 3) primary syngenetic but epigenetic to present site.

5. Clastic-sedimentary units within the volcanic columns represent contemporary erosional products of subjacent volcanics. They tend to be erratic in thickness, composition, and distribution. As such, they are of limited value for purposes of stratigraphic correlation across broad regions.

These conclusions together form a working hypothesis which is now applied, in illustration, to a generalized interpretation of adjoining portions of the Shield.

SUPERIOR-TIMISKAMING REGION

Introduction

The portion of the Canadian Shield herein referred to as the Superior-Timiskaming region extends from Lake Winnipeg on the west to the Grenville "front" on the east, a distance of 960 miles, and from James Bay on the north to Lake Huron on the south, a distance of 360 miles. This region, which forms the southern portion of the Shield, is bounded to the north by rocks of similar character (the James Bay Paleozoic lowlands excepted), to the east by Grenville metamorphic rocks of uncertain relative age, to the south largely by younger Precambrian rocks of the Proterozoic division, and to the west by Paleozoic rocks of the Interior Plains (Fig. 4).

Archean segments are distributed indiscriminately across the region, in a variety of shapes and sizes, ranging from small, round segments less than 20 miles in diameter to long extensive belts more than 200 miles long. Most are aligned in a general east-west direction. Many segments are completely isolated whereas others are joined one to the other by narrow, tenuous ribbons of Archean rocks. For present purposes, Archean rocks have been arbitrarily divided into 15 segments as illustrated in Figure 4 and listed in Table 1.

General Geology

Archean segments and intervening masses of younger granite form a basement complex upon which younger Precambrian rocks of Proterozoic age (40, 1958) rest with profound unconformity. The Proterozoic rocks lap up on the south flank of the region and locally form northward projecting tongues such as occur at Lake Nipigon and Cobalt.

Rock types, structure and mineralization of the segments are listed in Table 1 (also, see 15). In general, Archean rocks of the region have in common the following features: 1) Assorted acid to basic volcanic flows and pyroclastics (Keewatin-type) predominate; 2) conglomerate-shale-graywacke units (Timiskaming-type) are closely associated; 3) banded iron formations are common; and 4) acid to intermediate intrusive stocks with associated mineral deposits are contained in the volcanic-sedimentary columns. These features are briefly summarized in the following paragraphs (local references are cited in Table 1).

1. Andesite-basalt volcanics far exceed acid volcanics in volume and distribution. Basaltic volcanics predominate in some areas (e.g. Opasatika area) whereas andesites predominate elsewhere (e.g. Chibougamau). The proportion of intercalated acid volcanics ranges from negligible (Malartic

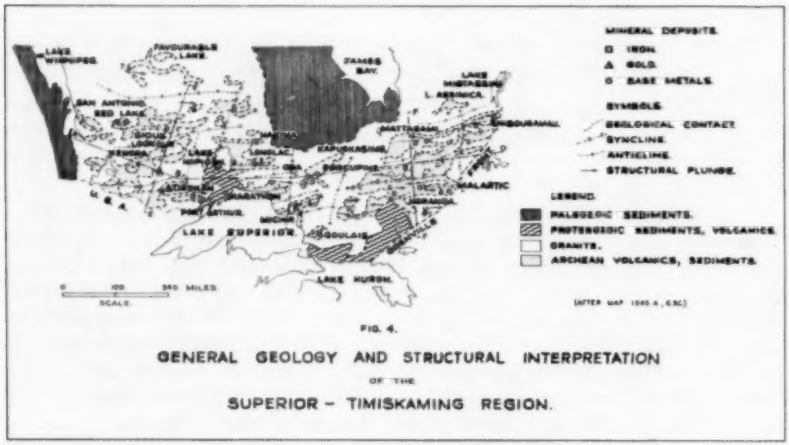
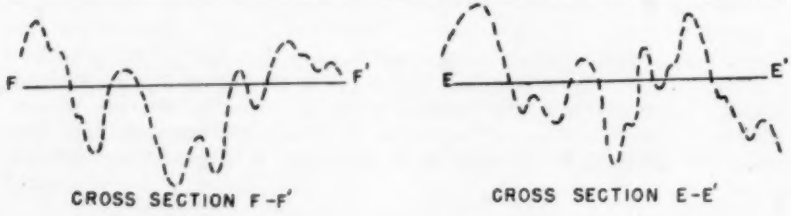


FIG. 4.

GENERAL GEOLOGY AND STRUCTURAL INTERPRETATION OF THE SUPERIOR – TIMISKAMING REGION.



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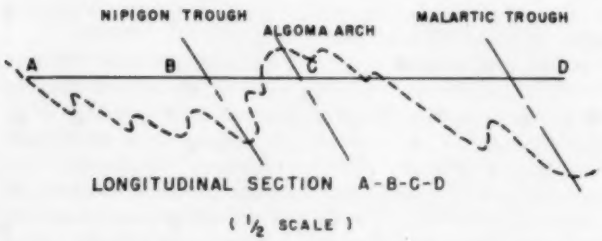

LONGITUDINAL SECTION A-B-C-D

(½ SCALE)

FIG. 4. General geology and structural interpretation of the Superior-Timiskaming region.

TABLE I

Archean segment	Rock types	Structure	Mineralization
1. San Antonio (Stockwell, C. H., C.I.M., 1948, p. 306–314)	Rhyolite, trachyte, andesite volcanics. Cgl.-arkosic qte. Gabbro-diorite sills & dikes. Porphyry-felsite dikes.	Volcs. & seds. compressed into NW–SE folds. Gentl ‹ SE plunge at Rice Lake-Beresford Lake area.	*gold*—Au-qtz veins in diorite sills.
2. Red Lake-Lake St. Joseph (Barrett, R. E., C.I.M., 1948, p. 368–372) (Bruce, 1935) (Horwood, H. C., C.I.M., 1948, p. 322–328)	Assorted acid to basic volcanics. Cgl-sh-gwke. Banded I.F. in both volc. & seds. Qtz. porphyry, granite, diorite stocks.	Volc. & seds. compressed into E–W folds. Dominant E plunge at Red Lake & Pickle Crow.	*gold*—Au-qtz-CO_3 veins in porphyry stocks, volcs & siliceous seds. *iron*—magnetite I.F.
3. Lake of the Woods-Dryden (Suffel) (Greer)	Assorted acid to basic volcanics; abundant acid pyrocl. Cgl-sh-gwke. Granite porphyry, felsite & diorite stocks & sills.	Volc. & seds. compressed into E–W folds. Variable plunge, i.e. undulating fold pattern.	*gold*—Au-qtz-$FeCO_3$-py veins near, or in, granitic stocks.
4. Atikokan-Kaministikwa (Bruce, 1933)	Basalt-andesite-rhyolite volcanics. Cgl-sh-gwke. Banded I.F. Granite porph., felsitic & basic intrusives.	Volc. & seds. compressed into E–W folds. 35 degree E plunge at Shebandowan.	*gold*—Au-qtz veins + Pb-Zn-Cu-S. *iron*—Magnetite I.F.; oxide I.F. at Steeprock. Titaniferous mgt. Cu-cpy replacement bodies at Shebandowan.
5. Nipigon-Longlac (Horwood, H. C., C.I.M., 1948, p. 377–385)	Mainly andesite flows & pyrocl. with thin beds black slate & I.F. bands. Cgl.-gwke-arkose-qte + I.F. bands. Qty. porphyry intrusives.	Volc. & seds. compressed into E–W folds. 16–60 degree W plunge.	*gold*—Au-qtz-py-cpy in porphyry dikes & stocks. *iron*—magnetite I.F. in seds.
6. Marathon (Pye)	Mainly andesitic flows & pyrocl. Gwke-sh-I.F.—metamorphosed. Granite, syenite & qtz. porph. intrusives.	E–W folds. 20–30 degree E plunge at Manitouwadge.	*gold*—Au-qtz-py-cpy veins near qtz porph. stock. *Zn-Pb-Cu*—disseminated sulfides in sed. cherts.
7. Michipicoten (Collins and Quirke) (Moore and Armstrong) (Goodwin)	Andesite to rhyolite flows & pyrocl. + I.F. Cgl-sh-gwke + I.F. Qty. porph., granodiorite stocks.	E–W folds. Variable plunge i.e. undulating fold pattern.	*gold*—Au-qtz-py-cpy veins in & near granite stocks. *iron*—siderite-py-hematite in I.F.

Abbreviations used in Table I: cgl—conglomerate; volcs—volcanics; seds—sediments; qtz—quartz; I.F.—iron formation; py—pyrite; mgt—magnetite; cpy—chalcopyrite; pyroc—pyroclastics; gwke—greywacke; arseno—arsenopyrite; pyrrh—pyrrhotite; qte—quartzite; sh—shale.

TABLE I (*Continued*)

Archean segment	Rock types	Structure	Mineralization
8. Goulais (Moore and Armstrong)	Andesitic flows & pyrocl. + I.F. Cgl-gwke-qte-sh + banded I.F.	Compressed into E–W folds; variable steep plunge.	*iron*—magnetite I.F.
9. Swayze (Moore, 1926) (Rickaby) (Bannerman)	Andesite to rhyolite flow & pyrocl. + I.F. Cgl-qte-gwke-sh + banded I.F. Considerable acid volcanics. Granodiorite porphyry stocks.	E–W folds. E plunging syncline in S belt.	*gold*—Au-qtz-py veins. *iron*—siderite-py in I.F. magnetite I.F. *Zn-Pb*—sulfide veins in I.F.
10. Porcupine (Dunbar, W. R., C.I.M.J. 1948, p. 442–456)	Andesite-basalt-rhyolite flow & pyrocl. + I.F. Cgl-gwke-slate; in part, carbonaceous. Qty. porph., syenite & albitite intrusives. Diorite-gabbro intrusives.	Volc. & seds. compressed into E–W folds. 30–60 degree E plunge.	*gold*—Au-qtz-Ag-W-py-arseno veins in & near porphyry stocks.
11. Kirkland Lake (Thomson, J. E., C.I.M., 1948, p. 627–632)	Basalt-andesite-trachyte + I.F. Cgl.-sh-gwke. Syenite stocks; lamprophyre. Diorite to gabbro intrusives.	Volc. & seds. compressed into E–W folds. E plunging folds to E. W plunging porphyry stocks to W. Major E–W fault—S side up.	*gold*—Au-qtz-py-cpy veins in & near syenite stocks. *iron*—magnetite I.F.
12. Noranda (Wilson, M.E., C.I.M., 1948, p. 672–682)	Alternating belts andesite & rhyolite flows & pyrocl. Granite, granodiorite & diorite sills & stocks. Banded I.F. rare to absent.	East plunging anticlines & synclines. N.B. steep W plunge at Aldermac-Francoeur-12 mi. W.	*gold*—Au-qtz-py veins near porphyry. *Cu-Zn*—sulfide replacement bodies in pyrocl; qtz prophyry associated.
13. Malartic (Norman, G. W. H., C.I.M., 1948, p. 839–844)	Andesite-basalt-trachyte flows & pyrocl. Cgl-gwke-sh. Granite, granodiorite, diorite stocks & sills.	Volc. & seds. compressed into E–W folds. Variable plunge i.e. undulating. E–W Cadillac fault zone.	*gold*—Au-qtz-CO_3-py. *Zn-Cu-Pb*—sulfide replacement bodies in volc.
14. Mattagami (Latulippe)	Acid to basic lavas & pyroclastics. Cgl-sh-gwke. Banded I.F. in sediments to south. Granite, granodiorite, diorite, anorthosite sills & stocks.	Lavas, sediments, and basic intrusives folded into tight, E–W folds. New Hosco and Orchan deposits plunge W at 20–50 degrees.	*Cu-Zn*—sulfide replacement bodies associated with tuffs & agglomerates. *iron*—magnetite I.F.
15. Chibougamau (Mawdsley and Norman) (Derry, D. R., and Folinsbee, J.C.; C.I.M., 1957, p. 430–440)	Andesite flows & pyrocl.; minor rhyolite. Arkose-slate-banded chert. Diorite-pyroxenite-peridotite-anorthosite-gabbro sills.	Close spaced folds—E–W trend. Variable plunge.	*gold*—Au-qtz veins. *Cu*—Cpy-pyrrh-mgt-Au- veins in basic sills.

and Chibougamau) to significant (Noranda, Lake of the Woods); where acid volcanics are present, pyroclastic forms indicative of violent explosive activity are common. Trachytic volcanics are present locally (Kirkland Lake). The volcanic columns typically exhibit marked variation in lithology and structure over short distances. They, together with associated sediments, are commonly ascribed to rapid accumulation in mobile geosynclinal belts (Pettijohn).

2. The composition and texture of associated conglomerate-graywacke-shale units indicate that they were derived from older volcanics by rapid erosion and deposition in moderately deep water. The sedimentary units commonly contain volcanic flows, thereby indicating that active volcanism accompanied sedimentation. The sedimentary units are structurally conformable for the most part with enclosing volcanics; however, local angular unconformities have been demonstrated (Kirkland Lake, Red Lake).

3. Banded iron formations, which occur in both volcanic and sedimentary components of the segments, are common in all but the extreme eastern segments of the region (Noranda, Malartic, Chibougamau). Iron formations are characteristically composed of thinly banded chert, siliceous magnetite and jasper; some are composed of interbanded magnetite and shale, the chert content being low to negligible; others contain variable proportions of siderite and pyrite. Iron formations have been locally oxidized and enriched to form hematite-limonite deposits. Iron formations range in thickness from a few feet to many hundreds of feet. Thicker and richer portions locally constitute commercial deposits of concentrating ores.

4. Acid to basic intrusive stocks, dikes, and sills with associated mineralized zones are commonly associated with the volcanic-sedimentary columns. The stocks range from a few hundred feet up to several miles in diameter. Granite stocks are widespread (e.g. Red Lake, Marathon, Swayze, Noranda, and Malartic), as are quartz-porphyry (e.g. Red Lake, Marathon, Swayze, Noranda, Nipigon, Michipicoten, Porcupine) and granodiorite (e.g. Michipicoten, Noranda, Malartic). Syenite stocks are of more limited distribution (e.g. Marathon, Porcupine, Kirkland Lake). Diorite intrusives, though widespread, are particularly common in the Noranda-Malartic and Mattagami-Chibougamau segments. Intrusives of more basic composition such as anorthosite and peridotite, while sparingly distributed throughout the region, are common in the Mattagami-Chibougamau segments.

Mineralization is characteristically associated with intrusive stocks, dikes and sills. Gold-bearing quartz-carbonate veins with associated pyrite-sphalerite-galena-chalcopyrite commonly occur within, or marginal to, granitic intrusives in most segments; sulfide deposits (copper, Cu-Zn-(Pb)) occur as replacements of flows, breccias, tuffs and agglomerate commonly near diorite-gabbro intrusives (Noranda-Malartic), and as fracture fillings in diorite-gabbro-anorthosite sills (Chibougamau). Ore deposits are commonly ascribed to local structural controls with respect to location, form and extent, (preface to "Structural Control of Canadian Ore Deposits," Can. Inst. Min. & Metallurgy, 1948) and to nearby intrusives with respect to source (38).

Structural Interpretation

Folding.—Archean rocks have been complexly folded about east-west primary fold axes, on the one hand, and about northerly trending cross-fold axes on the other. Primary fold axes in the center and east portions of the region trend slightly north of east, whereas those to the west strike slightly south of east; the resulting regional pattern is thus slightly convex to the south (Fig. 4). In general, Archean segments are distributed along principal synclinal axes, whereas intervening belts of granite and associated quartz-mica schist are distributed along principal anticlinal axes. Gross (13) and Lowrie (18) have made similar interpretations for Archean rocks of north-western Ontario.

Major east-west trending fold axes are shown in Figure 4. In general, one or more synclinal axes extend through each Archean segment. Thus, principal axes extend through the 1) San Antonio-Red Lake-St. Joseph-Albany river, 2) Lake-of-the-Woods-Sioux Lookout-Armstrong, and 3) Atikokan-Longlac areas to the west, through 1) Marathon-Oba, 2) Michipicoten, and 3) Goulais areas in the center, and through 1) Mattagami-Chibougamau, 2) Timmins-Amos, and 3) Kirkland Lake-Noranda-Malartic areas to the east. Intervening anticlinal zones coincide with continuous or intermittent belts of granite and metasediments (Coutchiching-type).

Northerly trending cross-fold axes are delineated mainly on the basis of diverging east-west plunges. Data on structural plunge has been secured from regional maps as well as from structural sections of individual mines (Table 1). This information has been supplemented locally by reference to location of principal northerly-trending granite belts. Specifically, in the west portion of the region, extending from San Antonio on the west to Shebandowan on the east, recorded plunges are eastward; in the Nipigon-Longlac area to the east, on the other hand, plunges are westward. The two portions of the region thus appear to occupy opposing limbs of a northerly trending cross-syncline which is herein referred to as the Nipigon trough (Fig. 4). The presence of a subordinate anticlinal cross-fold immediately to the west is suggested by a persistent north-south granite belt that lies west of Lake Nipigon. In the interval from Longlac on the west to Kapuskasing on the east, recorded plunges are variable in direction, thereby indicating the presence of undulating folds such as occur in the Michipicoten area. These relations, together with the presence of relatively large and persistent granite belts thereabouts, suggest the presence of a cross-anticline, herein referred to as the Algoma arch (Fig. 4); the axis of the arch appears to pass approximately through the Michipicoten-Oba areas. To the east of Kapuskasing, recorded plunges are eastward, with local exceptions (e.g. Gogama, Kirkland Lake, Aldermac), as far east as the vicinity of the Grenville front; this portion of the region appears to lie on the west limb of a cross-syncline which is referred to as the Malartic trough (Fig. 4). Although the eastern limit of the west limb, hence the position of the cross-synclinal axis, is in doubt, local west plunges at Chibougamau suggest that it may lie in this vicinity as illustrated in Figure 4.

Faulting.—Faulting is not dealt with in detail in this paper. The main faults of the region, as shown on the Tectonic Map of Canada (prepared by the Geol. Assoc. of Canada, 1950), trend east-west, north-south, and, to a lesser extent, northeast-southwest. Principal east-west faults are the Porcupine-Beattie fault zone and Kirkland-Cadillac break in the east, and the Seine River break south of Atikokan to the west. The Kirkland-Cadillac break and associated faults are considered to have had a controlling influence on emplacement of gold deposits (C.I.M., 1948, p. 631). A northeast-southwest fault zone which passes through the Chibougamau area may have exerted similar control over base metal mineralization (C.I.M., 1948, p. 822). Although northeast-southwest faults are present along the Grenville "front" their magnitude and continuity have been questioned (39, p. 1414–1422).

Metallogenic Relations

Distribution and Nature.—The main metallogenic features of each segment are briefly summarized in Table 1. The intimate relationship between many mineral deposits and volcanic rocks is at once apparent. In general, gold deposits are widespread throughout the Superior-Timiskaming region, iron deposits are common in the interval from Red Lake on the west to Kirkland Lake on the east, whereas most base-metal deposits are concentrated in the eastern portion of the region (Noranda-Malartic and Mattagami-Chibougamau segments).

Interpretation.—Application of the working hypothesis previously presented to the Superior-Timiskaming region leads to the following interpretation:

1. In the interval from Red Lake on the west to Kirkland Lake on the east, iron and gold deposits are widespread and, in many instances, intimately related. Base-metal deposits of significant rank, on the other hand, are uncommon. This portion of the region accordingly constitutes an iron-gold metallogenic province. In contrast, in the Noranda-Malartic and Mattagami-Chibougamau segments, which form the eastern portion of the region, copper-zinc and gold deposits are common, whereas iron deposits are rare to absent. This portion of the region accordingly constitutes a copper-zinc-gold metallogenic province. Local exceptions occur near the margins of both provinces; for example, Shebandowan and Manitouwadge base-metal deposits lie at the south margin of the proposed iron-gold province, whereas the Atlin-Ruffner magnetite property is situated in the west portion of the Mattagami segment.

2. Mineralization in both provinces characteristically bears close spatial and genetic relationship to enclosing volcanics. Thus, most iron deposits occur in banded iron formations, which represent integral, syngenetic components of enclosing volcanic-sedimentary columns. Gold and base metal deposits, on the other hand, are commonly related to subvolcanic granitic and dioritic intrusive stocks. The close spatial and chemical relationships of extrusive volcanics and mineralized intrusive stocks suggests the possibility of common sub-volcanic derivation.

3. Within an individual Archean segment, mineral deposits tend to favor particular volcanic horizons (herein defined as encompassing volcanic extrusives, associated sediments, and subjacent intrusive stocks); the mineral deposits may be expected to occur, in particular, near centers of volcanic discharge.

4. Considering an individual Archean segment, volcanic extrusives, subjacent intrusives, sediments, and associated mineral deposits constitute a volcanic suite characteristic of that segment. The total volcanic suite, so defined, reflects the chemical composition of the parental magma from which that suite was derived. Insofar as Archean parental magmas varied chemically in time and space, the progenitorial volcanic suites varied accordingly. Metallogenic provinces, it is inferred, represent one manifestation of this variation.

CONCLUDING STATEMENT

The purpose of this paper has been to stress volcanic aspects of Archean "greenstone" segments. Development of a segment is viewed as a volcanic process which, once initiated, proceeded systematically through extrusive, erosional and intrusive phases to produce a total volcanic suite; individual components of the suite have unique characteristics, yet all are related by common magmatic derivation. Associated mineral deposits, it is suggested, should not necessarily be viewed as later, superimposed features, but rather as integral components of the particular volcanic suite. As stressed by Stanton (30, p. 28–29) the concept of volcanic derivation of ore deposits represents a development, rather than a contradiction, of established theories of igneous mineralization in that metal components are attributed ultimately to a magmatic source but are considered to have reached their present sites largely by way of the volcanic route.

Finally, it is to be stressed that the volcanic source horizon concept herein presented will be found to be applicable to many but by no means all mineral deposits in this large and ancient portion of the Shield.

ALGOMA ORE PROPERTIES, LTD.,
JAMESTOWN, ONTARIO,
Oct. 28, 1960

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GEOLOGY AND ORIGIN OF MINERALIZED BRECCIA PIPES IN COPPER BASIN, ARIZONA

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CONTENTS

	PAGE
Abstract	916
Introduction	917
Acknowledgments	918
General geology	919
Older Precambrian rocks	919
Late Cretaceous (?) or Early Tertiary rocks	921
Late Tertiary (?) and Quaternary rocks	923
Structure	923
Mineralized breccia pipes in Copper Basin	925
Shape	925
Relation to enclosing rocks	925
Nature of fragments	927
Associated mineralization	928
Structural considerations	930
Existing theories	931
Origin of Copper Basin pipes	933
Summary of data on origin of Copper Basin pipes	933
Interpretation of origin of pipes	934
Ore pipes versus barren pipes	934
Relation of mineralized breccia pipes to porphyry copper deposits	935
Ore deposits	936
Precambrian deposits	936
Laramide (?) deposits	936
Magnetic and soil sampling data	937
Late Tertiary (?) and Quaternary deposits	939
References	939

ABSTRACT

The Copper Basin district, Yavapai County, Arizona, contains a "porphyry copper" type copper-molybdenum deposit in which the bulk of ore mineralization appears to have been controlled by pipe structures. Mineralization is associated with a composite stock of presumed Laramide age which has intruded older Precambrian metamorphosed sediments and intrusive rocks. The Laramide stock is thought to have an elongated "beet" shape with a restricted orifice at depth. Its intrusive units range in composition from diorite to aplite, but mineralization appears to be most closely associated with quartz monzonite and quartz monzonite porphyry units. Mineral deposits of the district have a rough zonal arrangement with copper-molybdenum mineralization in the center surrounded by an aureole of lead-zinc-silver occurrences.

Mineralized breccia pipes are roughly cylindrical, near vertical structures ranging in diameter from 50 to 600 feet. A composite pipe is composed of a central core of heterogeneous, rotated, angular to rounded rock fragments surrounded by a zone of none-rotated crackle breccia. The fragments are cemented by quartz and may be mineralized with pyrite, chalcopyrite and molybdenite.

The pipes are thought to have been conduits through which late magmatic fluids, collecting near the restricted root of the stock, passed upward. An individual pipe was initiated by passage of fluid upward along a vertical line such as an intersection of faults or fractures. From this channel fluid worked into the adjacent fractured rocks and corroded fragments that were eventually loosened and moved in the conduit, gradually enlarging the pipe. Quartz later precipitated filling all of the open space and choking the conduit. Successive flexures of the stock or recurrent movement on regional-faults fractured this quartz in some of the pipes, and later hydrothermal solutions tended to follow these conduits, both because of their location on deep-seated structures and because the fractured quartz provided relatively high permeability.

Hydrothermal solutions, preceding and accompanying ore deposition, spread outward from the pipes and formed overlapping aureoles of alteration. Pyrite, chalcopyrite, and molybdenite were deposited along fracture surfaces throughout a large area in Copper Basin, but higher grade mineralization was generally confined to fractured pipe structures.

INTRODUCTION

THE Copper Basin district is located in central Arizona about 10 to 15 miles southwest of Prescott in Yavapai County (Fig. 1). The area is in the mountain region that separates the Colorado Plateau from the Basin and Range Province. The terrane is essentially a complex of igneous and metamorphic rocks of older Precambrian age intruded by a composite stock of Laramide (?) age and by late Tertiary (?) rhyolite.

Copper Basin is a north-trending oval shaped depression formed by differential erosion of the less resistant Copper Basin stock of Laramide (?) age from the more resistant older Precambrian rocks. Elevations range from 4,800 feet in the basin floor to 7,150 feet at the top of West Spruce Mountain at the northern edge of the district.

Major ore deposits of Precambrian age in nearby areas include the famous United Verde and United Verde Extension mines at Jerome about 25 miles to the northeast and the currently active Iron King mine near Humboldt, about 15 miles to the east (Fig. 1). Bagdad, a porphyry copper deposit of Laramide (?) age is about 35 miles west of Copper Basin. Numerous smaller mines and prospects are present in widely distributed mining districts in the region, many of which have not been studied in detail or classified. Prior to this investigation, Copper Basin was one of the little studied districts, although it has a long history of sporadic production of copper, lead, zinc, gold, and silver from deposits of different ages and different structural settings. Of particular interest is the origin of the mineralized pipe-like ore bodies. Although production to date probably has not exceeded $3,000,000, larger deposits of low-grade copper-molybdenum ore are known.

Johnston's (13) original work in Copper Basin, from which much of this paper is taken, classified the igneous and metamorphic rock types in space and time, related the ore deposits to this classification and described the pipe-like deposits as to significant features of origin and mode of emplacement. Lowell, who has spent much time in active exploration in the district, contributed information on the mineralogy and structure of the breccia pipes from detailed mapping and drilling data.

The first general study of the region, including the northern half of Copper Basin, was published by Wheeler (23) in 1876. References to Copper Basin are included in a reconnaissance of quicksilver prospects by

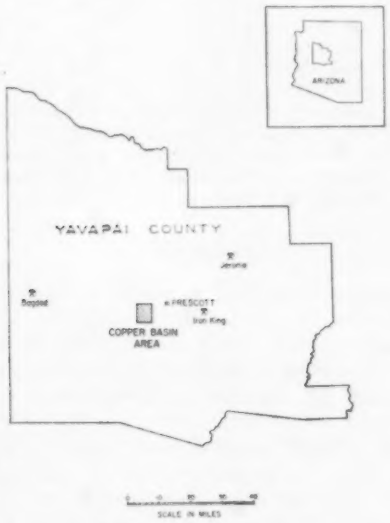

FIG. 1. Index map.

Lausen and Gardner (14) and a description of the placer deposits by Wilson (24). Anderson (1) has prepared a U. S. Geological Survey open file report on the Loma Prieta mine.

Acknowledgments.—Part of this paper is taken from a Ph.D. thesis submitted to the University of Utah by the first named author, who is greatly indebted to Dr. A. J. Eardley, Dean of the College at the University of Utah, under whose supervision the research was conducted. The criticisms in the field of Dr. C. A. Anderson and Dr. Medora Krieger of the United States Geological Survey are greatly appreciated. Thanks are due the officials of Phelps Dodge Corporation and Ranwick, Inc. for permitting access to their properties. Messrs. Fred Gibbs and Fred Schemmer, local property owners and mine operators, gave freely of their knowledge of the district. Thanks are due Dr. T. F. O'Neill and Mr. Hollis G. Peacock for criticism of this manuscript and contributing many valuable suggestions.

GENERAL GEOLOGY

The igneous-metamorphic terrane of the Copper Basin area poses a difficult problem in the establishment of a definite time classification because there are no sedimentary marker beds present. A tentative three-fold classification is presented consisting of (1) metasediments and igneous rocks of older Precambrian age, (2) composite stock and dike rocks of late Cretaceous (?) or early Tertiary (?) age, and (3) a rhyolite sequence of late Tertiary (?) age (Fig. 3). The precise age of igneous rocks in this region will ultimately depend upon a comprehensive program involving modern age determination methods.

FIG. 2. View of Copper Basin looking west. 1. Red Hill pipe, 2. Copper Hill pipe, 3. Quartz Hill pipe, 4. Smelter Hill pipe, 5. Commercial pipe, 6. Red Bird pipe, 7. Victoria pipe, 8. Loma Prieta dump, 9. Rhyolite plug, 10. Rhyolite volcanic neck.

Older Precambrian Rocks.—The sequence of metamorphic and igneous rocks designated as older Precambrian include, from oldest to youngest, a metasediment unit, amphibolite unit, and four units of granitic igneous rocks mapped as quartz diorite, granodiorite porphyry, aplite, and granodiorite (Fig. 3). There is no definite proof within the Copper Basin district of the age of these rocks, but Anderson and Creasey (4, p. 46) have demonstrated the Precambrian age of similar rocks that lie under sandstone of Cambrian age in the Jerome area.

Metasediments are present as one large unit near the Boston-Arizona mine and as small xenoliths and roof pendants throughout the district (Fig. 3). Textural types observed in this unit include argillite, slate, phyllite, hornfels, and, locally, schist. The original sedimentary rocks were, for the most part, probably bedded andesitic tuffs, siliceous shales, and fine-grained sandstones. A few bands of gray, dense limestone, less than 6 inches thick, are intercalated with siliceous beds in Finch Wash about an eighth of a mile north from the rhyolite tuff unit (Fig. 3).

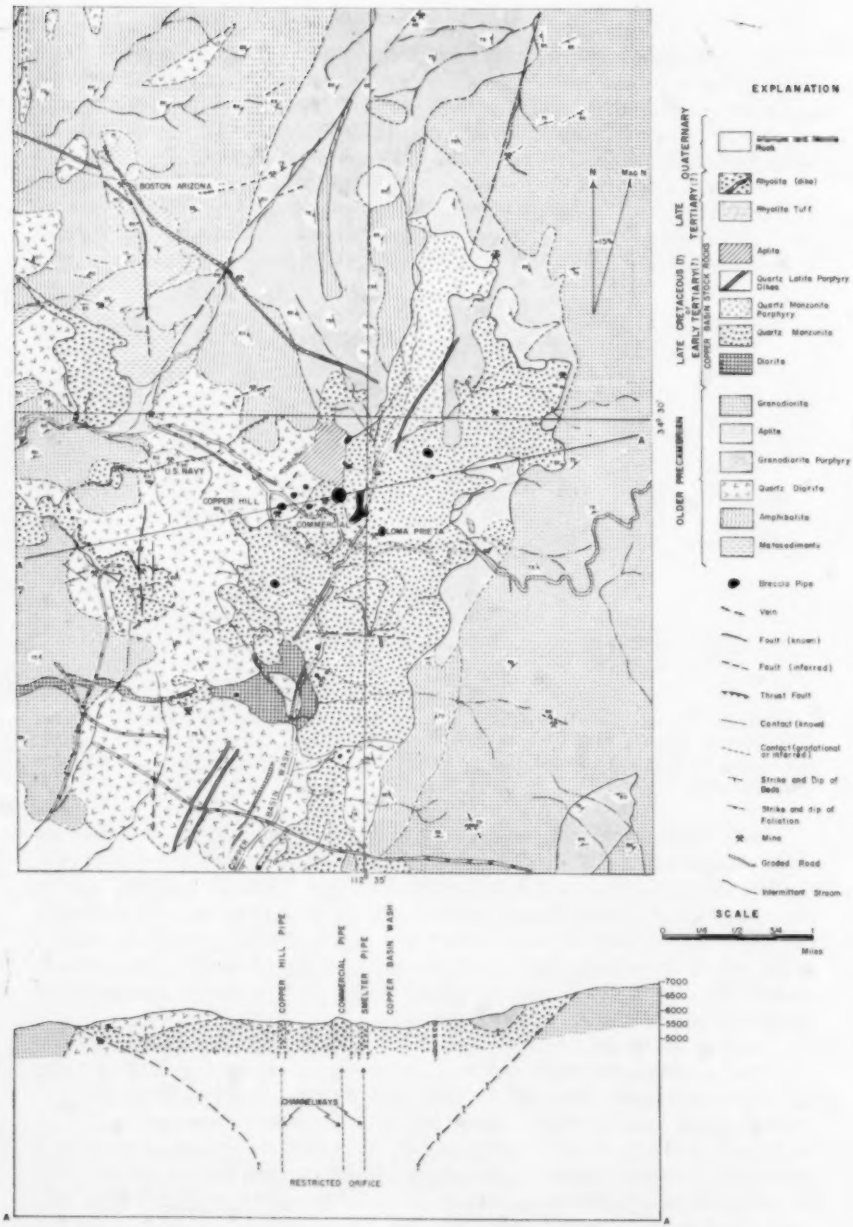

FIG. 3. Geologic map and cross section of the Copper Basin mining district, Yavapai County, Arizona.

The amphibolite unit embraces a variety of basic rock types covering a large part of the northern half of the area and one elongate band bordering the east side of the Copper Basin stock. This unit comprises a basic assemblage of rocks in which medium to coarse grained amphibolites dominate, but fine grained basic and siliceous bands are common. Dikes ranging from ultra basic to aplitic types are abundant in this unit. Much of the banded rock within the amphibolite is suggestive of original andesite and basalt flows separated by tuffaceous beds, but no relict pillow structures as described by Anderson and others (3) at Bagdad were observed. Some irregular shaped bodies probably represent basic intrusives.

Quartz diorite, presumed to be the oldest of the granitic units, is represented by one large mass and many smaller bodies in the western half of the district. The central part of the larger mass is relatively uniform in texture and composition, but the contact zones are commonly interfingered with the metasediment and amphibolite units. A foliation, ranging from barely perceptible to schistose was observed in all exposures. Metamorphism has affected much of this unit, but the comparatively fresh rock is composed of andesine feldspar, quartz, orthoclase, hornblende and accessory minerals including magnetite, zircon, apatite, augite and sphene.

Precambrian granodiorite porphyry occurs as a large mass in the north-central part of the area and as isolated bodies east of Copper Basin. A definite foliation is present which ranges from a barely perceptible planar direction to a strong foliation dominating the rock appearance. This unit includes rocks ranging in composition from quartz diorite to granite; however, about 75 percent is composed of a coarse grained granodiorite porphyry containing large zoned plagioclase crystals set in a matrix of alkaline feldspars, quartz, hornblende and biotite. Contact metamorphic and aplitic borders are common along contacts of this unit and the older rocks. The three aplite bodies shown as of Precambrian age on Figure 3 appear to be closely related to the granodiorite porphyry.

The granodiorite unit is a comparatively uniform granitic-textured rock bordering the entire eastern side and part of the southwestern side of the district. Some foliated border zones are gradational with other units and contain numerous basic clots, but the interiors of the large bodies are free of perceptible planar features and in the field appear similar to igneous rocks younger than Precambrian. However, in thin section much granulation and mortar structures are apparent in most of the minerals and strong undulatory extinction is apparent in the quartz. Minerals present include oligoclase-andesine, orthoclase, microcline, quartz, biotite, hornblende, iron ores, sphene, zircon, and augite.

Late Cretaceous (?) or Early Tertiary (?) Rocks.—The composite Copper Basin stock, which is irregular in outline and approximately 5 miles long and one mile wide, occupies the floor of the north-trending, oval-shaped Copper Basin. Apophyses of the stock occur in small circular depressions west of the main basin (Fig. 3). The Copper Basin stock has been divided into the following intrusive units from oldest to youngest: diorite, quartz monzonite, quartz monzonite porphyry, quartz latite porphyry, and aplite.

Direct evidence is lacking for a definite age for the Copper Basin stock rocks, however, a late Cretaceous (?) or early Tertiary (?) age is suggested on the basis of the following facts and inferences:

(1) The composite stock intruded all of the Precambrian units as mapped.
(2) The stock rocks show no indication of regional metamorphism.
(3) The general textural and structural features suggest a nearer-surface emplacement than the coarser-grained Precambrian rocks.
(4) The Copper Basin stock bears a striking resemblance to stock rocks of known late Cretaceous (?) or early Tertiary (?) age throughout the area bordering the Colorado Plateau and specifically those at Bagdad, only 35 miles to the west, as described by Anderson and others (3, p. 21–25).
(5) A pyrite-chalcopyrite-molybdenite mineralization, closely associated with the Copper Basin stock, is remarkably similar in character to mineralization in porphyry copper deposits in the Southwest, none of which have been assigned a Precambrian age.

It was found in thin sections that Copper Basin stock rocks could be separated from the adjacent Precambrian igneous rocks on the basis of lack of undulatory extinction in quartz in the younger rocks.

The earliest intrusive assigned to the Copper Basin stock is a fine-grained, dark green diorite plug exposed on the southwest side of the basin. The diorite is composed essentially of andesine feldspar and hornblende. Minor accessory minerals include zircon, apatite, and magnetite.

Quartz monzonite, the largest intrusive unit of the Copper Basin stock, occupies the central floor of the basin. This rock is the least resistant to weathering of any of the igneous rocks in the area and most of the unit is covered by residual soil and by terrace gravels along and east of Copper Basin Wash. The general rock type is a fine to medium-grained, equigranular biotite quartz monzonite, which grades transitionally into a fine-grained hornblende border facies; however, a slightly porphyritic facies is locally present. It is likely that this unit is composed of multiple intrusions instead of one individual intrusive. The rock is composed essentially of andesine, orthoclase, quartz, biotite, and locally hornblende. Minor accessory minerals include apatite, zircon, and iron ores. Of interest is the lack of strain shadows, granulation, and mortar structures in the minerals.

The next youngest intrusive, a light to medium gray quartz monzonite porphyry, is present in the north end of Copper Basin as an elongate band averaging about 1,500 feet wide and some 2 miles in length. The quartz monzonite porphyry exhibits relatively sharp contacts with adjacent rocks. These contacts are marked locally by intrusive breccias. Oligoclase-andesine and biotite phenocrysts compose about 30 percent of the rock and the remainder is a fine-grained equigranular mosaic of oligoclase-andesine, orthoclase, quartz, biotite, and minor accessory minerals including magnetite, zircon, and apatite. Oligoclase-andesine phenocrysts range from 2 mm to 2 cm and average about 5 mm, and biotite, in hexagonal plates, ranges from 1 to 4 mm in diameter and averages about 2 mm.

Porphyry dikes, having a wide range in texture and composition, are included as quartz latite porphyry. Many of these dikes are identical in composition with the quartz monzonite porphyry and are similar texturally

except the groundmass is much finer-grained. One major trend of these dikes is N 20° E, parallel to the long axis of the quartz monzonite porphyry body and continuous to the south at least 3 miles beyond this unit. One quartz latite porphyry dike, traced from Copper Basin for 2 miles northwest to beyond the Boston-Arizona mine, was indispensable in interpretation of some structures and the age of ore deposits. A close spatial relation exists between the quartz latite porphyry dikes and the copper-molybdenum mineralization. The dikes range in color from light to dark gray and show a mottled appearance due to the large white feldspar phenocrysts. The darker color of some of the dikes may be due to a finer-grained groundmass or more mafics in the groundmass. Phenocrysts of feldspar, biotite, and hornblende form from 10 to 30 percent of the dike rock, and the remainder is a fine-grained to microgranular mosaic of feldspar, quartz and mafic minerals.

Small bodies and dikes of white to pale pink, non-foliated aplitic rocks cut all of the Copper Basin stock rocks, but no evidence was found to indicate that all of this aplite is of the same age. Many small bodies of aplite found near the quartz monzonite may have formed at essentially the same time. Normal pegmatites are rare in the area of Laramide (?) rocks; however, small masses and veins of coarse glassy quartz are present, which locally contain microcline or perthite crystals as much as one inch long.

Late Tertiary (?) and Quaternary Rocks.—Rhyolitic rocks of late Tertiary (?) age include a volcanic neck, two rhyolite plugs, numerous dikes, and one small exposure of bedded tuff (Fig. 3). The high rugged buttes, forming a landmark on the west side of the district, represent a volcanic neck consisting of breccia, blocks of bedded tuff, and much intrusive rhyolite. Two rhyolite plugs form conspicuous light colored hills in central Copper Basin within the area of the composite Laramide (?) stock. Rhyolite dikes are prominent in Copper Basin and a rhyolite and rhyolite breccia dike "swarm" is present in the extreme southwest part of the map area (Fig. 3).

The rhyolite intruded all of the Copper Basin stock rocks, and mapping suggests a period of erosion separates the two periods of intrusion. The distribution of the bedded tuff, which fills canyons adjacent to the volcanic neck near the western border of the district, indicates there has been little change in the surface features since deposition.

Quaternary deposits are surficial accumulations of unconsolidated or semiconsolidated alluvium, terrace gravels, talus, and mantle rock. Stream terrace material, associated with Copper Basin Wash and tributary gulches, is irregularly distributed on the floor of Copper Basin. The terrace gravel, attaining a maximum thickness of 35 feet, is composed of a heterogeneous mixture of material ranging from stream boulders 3 feet in diameter to a coarse to fine-grained sand and clay matrix. These gravels are of importance in that they contain oxidized copper deposits and some of the gold placer.

STRUCTURE

The Copper Basin district has undergone a complex structural history since early Precambrian time, and interpretation is difficult since regional de-

formation and several periods of igneous intrusion have obscured much of the evidence.

Foliation in the Precambrian rocks in areas not disturbed by faulting or intrusion strikes north to N 30° E and dips steeply westward in general conformance with the regional folding in older Precambrian rocks in Arizona as described by Anderson (2). The foliation has imparted a definite grain to the country and has exerted a profound influence on the subsequent intrusive and structural history.

Two distinct fault-fissure systems of Precambrian age are recognizable by steeply dipping tourmaline-quartz veins: one set strikes N 60°–75° W, and the other strikes N 55°–70° E. Two faults of probably regional magnitude, exposed in the northern half of the area, pre-date the Copper Basin stock rocks and may have had their origin in Precambrian time. The westernmost of these faults strikes N 30°–40° E and displaces a Precambrian quartz vein laterally about 2000 feet but does not displace a Laramide (?) quartz latite porphyry dike (Fig. 3). The easternmost of these two faults strikes N 10°–20° E and can be traced as a lineament on air photos for several miles north from Copper Basin. Since these two regional (?) faults strike more or less parallel with the foliation direction, the magnitude of displacement could not be ascertained within the area mapped.

The easternmost regional (?) fault and the foliation direction are thought to have been important in controlling the emplacement of the Copper Basin stock. The southward extension of this fault parallels the longitudinal axis of the Copper Basin stock and one major trend of quartz latite porphyry dikes. The junction of several Precambrian units may have helped serve as a structural locus for point of entry for the stock (Fig. 3). The large massive block of granodiorite on the east side of Copper Basin may have helped concentrate later structures along its western contact. A thrust fault that is well-exposed in the U. S. Navy mine has been intruded by quartz monzonite. This fault probably originated in the thrusting aside of the west wall by the intrusion of the Copper Basin stock.

The east contact of the quartz monzonite unit dips 45°–60° west toward Copper Basin. The contact of this same intrusive on the west side of the basin is essentially horizontal and represents the stock roof in this area. The true west contact of the stock is thought to be marked by the quartz monzonite occupying the east-dipping thrust fault a mile west of Copper Basin. These data suggest that the quartz monzonite could be a funnel-shaped stock or ethmolith having a restricted "nozzle" or "root" occupying a central position and extending in depth to the original underlying magma chamber (Section Fig. 3). The "root" is visualized as being elliptical in plan and having an elongation in a N 10°–20° E direction. It is further suggested that the individual intrusives of the composite stock pushed their way up through the restricted orifice and expanded in the direction of least resistance at that particular time.

A north-trending, steeply dipping fault zone on the west side of the district was traced for some three miles from the Boston-Arizona mine on the north to about a mile south of the U. S. Navy mine. The most pro-

ductive zinc, lead, and silver deposits are closely associated with this fault. Ore within the fault zone is of a later age than the quartz latite porphyry dike at the Boston-Arizona mine. However, a post-mineralization period of faulting along this same zone produced a horizontal displacement in the quartz latite porphyry dike of about 1,200 feet in the mine area.

Numerous faults of small displacement are associated with and parallel to most of the previously discussed structures. Certain of these faults are of importance as ore controls within the Copper Basin stock and may represent minor adjustments of regional faults or movements within the magma chamber after solidification of the roof portion. Prominent minor fault trends observed within Copper Basin are as follows: 1 N 10–30° W; 2 N 10–30° E; 3 N 70–80° E; 4 N 60–80° W.

Prominent joint sets are parallel to the above fault systems, although many joints appear to have random orientation. Some of the minor faults are occupied by late Tertiary (?) rhyolite dikes and some have post-rhyolite displacement.

MINERALIZED BRECCIA PIPES IN COPPER BASIN

Some 25 exposed mineralized pipes are associated with the Copper Basin stock rocks within Copper Basin (Figs. 2, 3, 4). The main cluster of pipes, including the productive ones, form round reddish brown hills on the west side of Copper Basin north of the main road. The Commercial, Copper Hill, and Loma Prieta mines have exploited three separate pipes to depths ranging from 300 to 600 feet. The Commercial mine has supplied most of the copper ore produced from the district.

Most of the pipes are resistant to weathering and protrude above the basin floor as low round hills having a relief of less than 300 feet. However, the Loma Prieta and several other pipes on the east side of Copper Basin Wash have no topographic expression.

Shape.—Most of the pipes appear to be nearly vertical columnar bodies having a roughly circular or elliptical plan, although some have irregular projections on one or more sides. Pipes where exposed by mine openings and drill holes range in diameter from 50 to 600 feet. The largest pipe, having a diameter of about 600 feet, is developed by the Commercial mine. The Loma Prieta and Copper Hill mines have explored pipes approximately 300 feet in diameter. Numerous small exposures of breccia may represent pipes in the early stages of development, and in one locality a single rotated fragment was observed at a joint intersection.

Vertical changes in shape could not be determined from the limited exposures, but it is likely that the pipes will show irregularities in depth. Exploration data indicate that the Loma Prieta pipe retains a cylindrical shape to a depth of at least 400 feet. Two small pipes appeared to bottom, locally at least, on flat faults, but the relationships are uncertain.

Relation to Enclosing Rocks.—The pipes are spatially related to the composite Copper Basin stock of postulated Laramide (?) age. The main group of strongly mineralized pipes are clustered around the south contact of the quartz monzonite porphyry unit, but none occur wholly within this rock

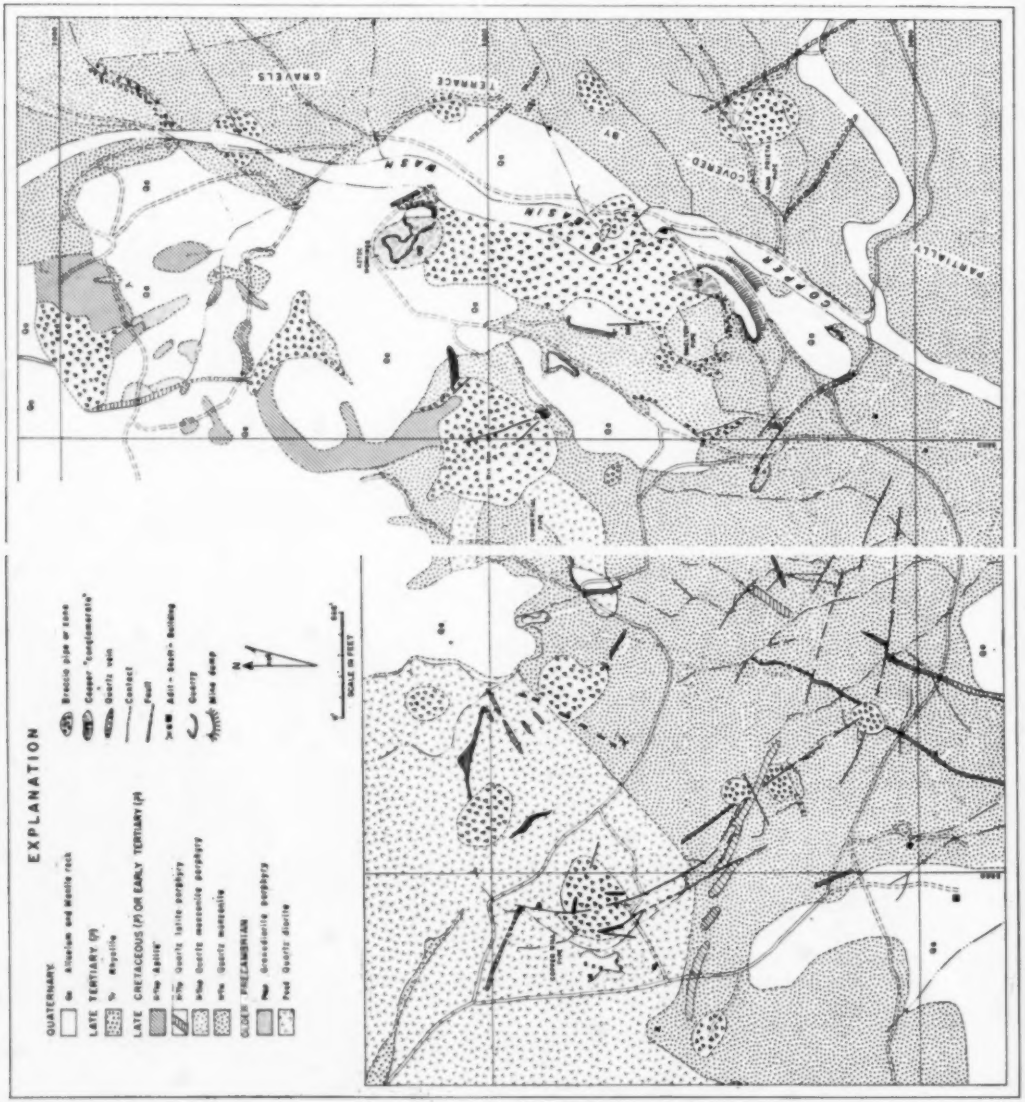

FIG. 4. Geologic map of main breccia pipe area, Copper Basin mining district.

(Fig. 4). The main pipe-like body at the Commercial mine is located at the junction of several rock types including quartz monzonite, quartz monzonite porphyry, quartz latite porphyry, and aplite, all of Laramide (?) age, and quartz diorite of Precambrian age. Several pipes, including the Loma Prieta, are entirely within the quartz monzonite unit. The Copper Hill and two adjacent pipes are in Precambrian quartz diorite at the surface but drilling and underground workings expose the quartz monzonite unit in depth.

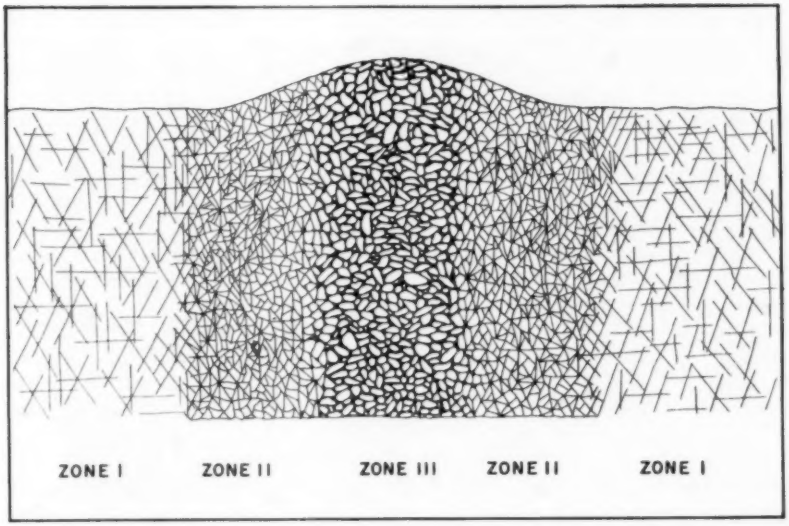

FIG. 5. Idealized diagram of Copper Basin Breccia Pipe. Zone I—Mineralized joint and fracture system. Zone II—Angular "crackle" breccia cemented by quartz and sulfides, no marked rotation or mixing of fragments. Zone III—Angular to rounded "boulder" breccia exhibiting marked rotation and mixing of fragments. Cementing materials (black) are quartz and sulfides. Zones II and III, combined, range from 50 to 600 feet in diameter.

Fragments from all of the intrusive rocks of the Copper Basin stock were found in some of the pipes indicating that, in general, pipe formation followed the stock intrusion. The rhyolite dikes cut the pipes and associated mineralization and are thought to be much later in age.

Spatial distribution of the pipes appears to be a critical factor in the question of origin. The main group, including all strongly mineralized pipes, is located directly above the postulated position of the restricted orifice or root area through which the separate intrusions that formed Copper Basin stock rocks are thought to have been injected.

Nature of Fragments.—Individual fragments show a wide diversity in size, shape, and composition within each pipe, and their physical properties

can be best understood by discussion of the different zones shown on the idealized diagram (Fig. 5). Locally the contact between two zones is sharp, but in general the contacts are gradational and somewhat arbitrary.

Zone I represents fractured and jointed ground adjacent to the pipes and in the inter-pipe areas, and, although it is rather ill-defined, it roughly includes most of the area shown in Figure 4. Smaller areas representing Zone I are present around the non-productive pipes in South Copper Basin. It comprises closely-spaced joints, fractures, and minor faults that have been partially mineralized by vein quartz, pyrite, and chalcopyrite, or by their oxidized equivalents. The host rock is slightly to moderately altered by conversion of mafic minerals to mica and by argillic and sericitic alteration of feldspars. Certain joint and fracture sets dominate within small areas, but no definite overall pattern was determined. The dominant joints and fractures are normally spaced from about 3 inches to 3 feet apart; however, when the rock is broken, numerous irregular, incipient, iron-stained cracks become apparent. There is little or no rotation of the joint and fracture blocks in Zone I.

Zone II is characterized by angular to sub-angular fragments ranging from 1 inch to 10 feet in diameter but in general averaging between 2 to 12 inches. There is no marked rotation or mixing of fragments although some movement has taken place in parts of this zone, probably by subsidence or dilation. The non-rotational character of the fragments is indicated by the common attitude of the foliation in Precambrian quartz diorite in the Copper Hill adit. Much of this zone resembles the stockwork breaking or "crackle" breccia of the porphyry copper deposits. An individual fragment may be transected by a finer network of fractures. The fragment size is normally smaller than in Zone I and non-rotational movement locally obscures the original pattern of joints and fractures; however, parallel fissures occupied by vein quartz and sulfides do occur in this zone. The mineralization in general is much more intense than in Zone I, including stronger wallrock alteration and more quartz and sulfides cementing the fragments.

Zone III, where present, represents the innermost or central zone of the pipes as shown on Figure 5. This zone is commonly composed of a heterogeneous mixture of fragments showing marked rotation. The fragments are rounded, sub-rounded, or angular and are about the same size as in Zone II. Many of the rounded or sub-rounded fragments have been cracked into smaller angular pieces by incipient fractures. The rounded fragments resemble stream boulders and can best be described as "boulder" breccia. Sharp contacts generally separate Zones III and II, but some contacts are gradational over a width of 10 to 30 feet. Zone III is not exposed or could not be recognized in many of the pipes but is well-developed in the Loma Prieta (1), Copper Hill, and parts of the Commercial mine. Figure 6 shows the rounded to sub-rounded fragments of gneissic Precambrian quartz diorite mixed with Laramide (?) quartz monzonite fragments and cemented by quartz and sulfides.

Associated Mineralization.—An interesting feature of the Copper Basin pipes is that the fragments are generally cemented by quartz and minor

amounts of other minerals and not by igneous material or finely ground rock derived from the fragments themselves.

Quartz deposition ranged from pervasive silicification, to partial replacement of fragments, to filling of pre-existing open spaces. Much structural adjustment took place during mineralization, and recementing of earlier quartz by later quartz is common. It appears that the replacement quartz formed at an early stage, probably in confined areas, whereas the inter-fragment quartz formed later in through-going trunk channels. There is

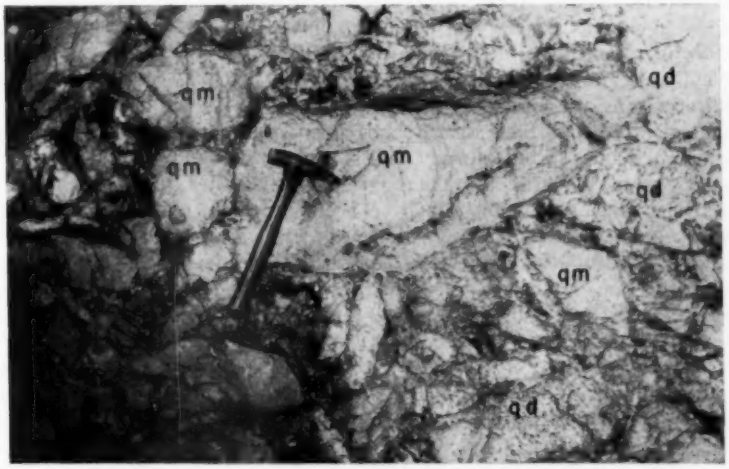

FIG. 6. Mixed rounded breccia fragments in Copper Hill adit level. Precambrian quartz diorite (qd) and late Cretaceous (?) or early Tertiary (?) quartz monzonite (qm) fragments.

some evidence suggesting that the following sequence of quartz mineralization may have taken place:

(a) formation of the main group of pipes in a cluster slightly over one mile in diameter (Fig. 4).

(b) choking of some pipes with replacement quartz. Those pipes west of Copper Basin Wash, in general, underwent more pervasive silicification than those east of Copper Basin Wash.

(c) introduction of inter-fragment quartz followed by copper and molybdenum mineralization in some pipes.

This process resulted in pipes in the northeast portion of the original cluster that received little quartz of either stage, pipes in the north central area that received first stage but little second stage quartz, the Loma Prieta pipe that received second stage but little first stage quartz, and the Commercial and Copper Hill pipes that received quartz of both stages.

Much of the replacement quartz is a white to gray, dense variety and is commonly associated with orthoclase. Both minerals, together or individually, replace fragments. Some of this material resembles aplite or alaskite and is quite similar to material described by Gilluly (8, p. 74–76) at the Ajo porphyry copper deposit. The elongate breccia mass about 600 feet east of the Commercial pipe is strongly silicified and original fragments can be distinguished only with difficulty.

The open-space filling type quartz is commonly granular to glassy in appearance. Some is coarse-grained, and crystals as much as one inch in long dimension were observed projecting into vugs between breccia fragments. A few lenticular veins of coarse glassy quartz as much as 10 feet wide are prominent in or near the pipes (Fig. 4) and narrow quartz veins are abundant in certain parts of some pipes. The massive glassy quartz locally contains a few isolated feldspar crystals.

Alteration, other than quartz and orthoclase described above, was not studied in detail. Iron-staining and secondary argillic alteration tends to mask the primary alteration in the oxidized zone. Where observed, it appears that the original mafic minerals have been bleached and altered to biotite, chlorite, and serpentine. Magnetite was altered to hematite and pyrite. Feldspars have undergone varying degrees of sericitization and local argillic alteration. Locally the original textures of the igneous rocks have been completely destroyed, but in general the alteration is weak to moderate. Where fragments are well-mixed there is a difference in intensity of alteration among adjacent fragments—probably due to original physical and chemical differences of the individual fragments. The quartz monzonite porphyry and quartz latite porphyry fragments were especially resistant to replacement and alteration.

Sulfides, essentially pyrite, chalcopyrite, molybdenite, and minor bornite, followed deposition of most of the quartz, and for the most part, were deposited in cracks and voids within the quartz. Minor blebs and veinlets of sulfide worked out into the altered rock fragments. In general the molybdenite appears to be somewhat later than the other sulfides and locally is concentrated in fractures devoid of other sulfides. It also shows less tendency than the pyrite and chalcopyrite to form "disseminated" mineralization surrounding strongly mineralized zones. The overall mineralization is remarkably similar to the common porphyry copper type in the Southwest. Minerals in the oxidized zone include limonite, jarosite, hematite, chrysocolla, chalcocite, cuprite, black copper oxides, native copper, malachite, azurite, and ferrimolybdite.

Normally the primary sulfide mineralization was concentrated in quartz cement and veinlets in Zones II and III; however, in cases where pervasive silicification has taken place in all or part of these zones there may be an increase in the concentration of ore minerals in the adjacent parts of Zone I.

Structural Considerations.—The pipes are within well-jointed, fractured, and faulted igneous rocks, and most pipes are located near the contact of one or more igneous rock units. It is probable that no single structural element is responsible for the location of the pipes.

Faults of known major displacement were not observed within the limits of the composite Copper Basin stock, but some could exist since much of this area is covered by mantle rock. As has been previously mentioned, a regional fault striking N 10–20° E is thought to have been a controlling factor in the emplacement of the stock. Two sets of fractures and faults striking N 10–30° W and N 10–30° E are prominent in the Copper Hill and Commercial pipes. Post-mineralization movement is evident in many of these faults, but numerous parallel quartz veinlets indicate an earlier origin. The N 10–30° E fault system controlled a main trend of quartz latite porphyry dikes thought to represent the last intrusives prior to mineralization. Faults striking N 60–80° W are prominent in and near some of the nonproductive pipes. It appears likely that fault, fracture, and joint intersections played an important role as initial loci for the trunk channels in the pipes. The more intensive fracturing in these intersection areas undoubtedly influenced the overall permeability and contributed to the fracture and brecciation pattern.

Three of the most strongly mineralized pipes are located at the contact of two or more igneous rocks. As shown on Figure 4, the Commercial pipe is at the junction of five igneous rock units including quartz latite porphyry dikes not shown on the map. The Loma Prieta and Copper Hill pipes are at the contact of at least two igneous units. These contact zones in conjunction with the faults, fractures, and joints may have also served as loci for pipe formation. However, the shape of the pipes and nature of the enclosing breccia does not suggest a simple tectonic origin.

Existing Theories.—The problem of origin and classification of steep columnar or tabular bodies of fractured or brecciated rock has received much attention in the literature. Some of the publications reviewing the literature or offering a classification have been written by Butler (5), Emmons (6), Kuhn (11), Walker and Walker (22), and McKinstry (19). The origin of most of the pipelike deposits has been explained by the following theories or by modification and/or combination of them: (1) explosion, (2) tectonic, (3) igneous intrusion, (4) fluid intrusion, (5) solution and replacement, (6)mineralization stoping, (7) shrinkage.

(1) Explosive action, generally thought to be associated with vulcanism, is responsible for openings (diatremes) blown out by gas. The openings may be filled with fragments of igneous material or country rock. Richards and Courtright (21) have suggested gaseous explosion for the origin of breccia pipes at Toquepala, Peru. Hack (9) and Lowell (18) have described characteristic features of diatremes in the Hopi Buttes volcanic field, Arizona.

(2) Tectonic breccia or fractured rock at the intersection of two or more faults or shear zones or at bends in faults may form columnar pipes. Commonly this type is irregular and changes notably as it passes from one wall rock to another. However, fault intersections are important as loci for pipes essentially formed by other agencies as described by Butler (5, p. 126)

in the San Francisco area, Utah, and Kuhn (11, p. 527) at Copper Creek, Arizona.

(3) The direct formation of breccia columns or dikes by the physical force of intrusion has been described by many authors. Lovering (16, p. 8) states:

> An intrusive push at a late stage in the solidification of a magma may cause the fracturing of a stock along lenticular or chimney-like zones that usually have their longest dimension parallel to the original platy structure of the intrusion. In such masses the small opening produced by intensive brecciation may be subsequently enlarged by reactive mineralizing solutions which dissolve some of the rock adjacent to the individual fractures—the first step in mineralization stoping as suggested by Augustus Locke.

Lovering (17, p. 12) has described some of the pebble dikes at Tintic, Utah, as representing material riding on top of monzonite or dragged along the edge of viscous monzonite bodies.

(4) Fluid intrusion has been advocated as another means of pipe or dike formation. This theory has much in common with the explosion theory but is apparently more restricted and has characteristic intrusive phenomena. The fluid involved is assumed to be gas or liquid of possible magmatic derivation but not magma as such. Farmin (7, p. 370) advocated the following for the pebble dikes at Tintic, Utah: ". . . fragments were broken from the underlying rocks by magma, or by fluids ejected from the magma during volcanism and were forced upward into rocks above by a relatively thick mud."

(5) Corrosion by ascending solutions was advocated by Butler (5, p. 126) for pipes in the San Francisco region, Utah as follows: "The rock has been brecciated apparently by slight movement, as no considerable fault can be traced from the ore zone. Solutions passing through this breccia zone have greatly corroded the rock, so that in places the fragments have the appearance of rounded boulders. In this manner the amount of open space must have greatly increased. Later this space was largely filled by ore and gangue minerals." Butler further suggested that the solutions were relatively confined and the dissolving action strong. Kuhn (11, p. 527) applied essentially the same theory to the pipes in Copper Creek, Arizona, but in addition emphasized simultaneous replacement.

(6) Locke (15) proposed the mineralization stoping theory to account for the formation of certain pipe deposits. This theory is somewhat analogous to the block-caving method of mining. Locke (15, p. 431) states that: ". . . removal of rock along trunk channels by rising solutions during an early stage of their activity, collapse and brecciation of the rock thus left unsupported, and deposition of ore and gangue minerals in the brecciated mass."

A prerequisite for application of this theory is proof for downward movement of the breccia mass.

(7) Hulin (10, p. 47) suggests the estimated 10 percent volume shrinkage on crystallization is responsible for much fracturing and brecciation in certain stocks or chonoliths. He states: "The result would be unsystema-

tized fracturing and shattering with attendant volume increase, structural features so characteristic of the porphyry copper ores. . . . In the absence of such autobrecciation the subsidiary ground might move downward within the limits of an encircling, crudely cylindrical fault surface, or within a nest of such surfaces."

Origin of Copper Basin Pipes.—In considering the origin of the roughly circular to elliptical pipelike deposits in Copper Basin it should be emphasized that other types of breccia and fractured ground are also present. All of the rock units of the Copper Basin composite stock are thought to have been intruded into their present position, and contact or intrusive breccia is present in many places. Since several pipes formed at intrusive contacts, some of the brecciation may have been inherited from previous intrusive phenomena, but this is not thought to be a critical factor in the origin of the pipes in general.

Fracturing and brecciation associated with faults were observed in many places, but these breccia zones are apt to be linear and highly irregular. However, faulting is assumed to have served as the original locus for at least some of the pipes, and fault breccia may have been present locally.

Summary of Data on Origin of Copper Basin Pipes.—The literature indicates that the origin of mineralized pipes is still a controversial subject. For this reason available factual information on Copper Basin will be summarized before an interpretation is given.

1. The pipes are spatially related to the composite Copper Basin stock and overlie the postulated orifice or root of the stock. They formed after solidification of all of the Copper Basin stock rocks but prior to the emplacement of the late Tertiary (?) rhyolite. The majority of the pipes were formed at the contact of two or more igneous rock units, though some were formed within one rock unit.

No faults of major displacement were observed in the vicinity of the pipes, but pronounced joint systems and minor faults are abundant. The two most important fracture directions appear to be N 10–30° W and N 10–30° E.

2. The pipes are roughly circular or elliptical in plan and appear to be near-vertical except for minor irregularities and displacements by post-pipe faulting. The depth extension is known only to a maximum of 600 feet.

3. The breccia fragments in the pipes range from about 1 inch to 10 feet in diameter, but the average size range is 2 to 12 inches. Fragments in Zone II are angular to sub-angular and those in Zone III are angular to well rounded. Movement in Zone III has been rotational and has resulted in the mixing of fragments (Fig. 5). The matrix surrounding the fragments is not composed of finely ground rock as is sometimes the case in other districts, but is made up principally of quartz. In certain pipes quartz, orthoclase and locally sericite, biotite and chlorite replace the borders of fragments. Pervasive silicification is present in some pipes, but more commonly quartz was deposited in interstices between fragments and in veinlets. A wide variation in the intensity of hydrothermal alteration of fragments is present. Comparatively fresh fragments of one rock type may be present near strongly altered fragments of another rock type. Alteration minerals recognized in the hypogene zone include quartz, orthoclase, sericite, clay minerals, chlorite, serpentine, biotite, calcite, hematite and pyrite.

4. Fracturing and faulting occurred after some quartz deposition and prior to the introduction of sulfides. Pyrite, chalcopyrite and molybdenite were intro-

duced later than most quartz mineralization and filled fractures and vugs in the quartz. Minor amounts of these sulfides were deposited in fissures and intergranular spaces in the fragments.

Interpretation of Origin of Pipes.—1. Pipe formation was associated with a late magmatic stage of the Copper Basin stock. Late magmatic fluids gradually concentrated around the root area of the composite stock after solidification of the roof portion and formation of a joint and fracture system.

2. Evidence is lacking as to the exact state and pressures of the early ascending fluids. It is assumed that the fluids gradually collected in several individual chambers in the vicinity of the composite stock root.

3. The fluids under high pressures ascended along the lines of least resistance which may have been fault or fracture intersections, openings along a single fault, or intersections of faults or fractures with igneous contacts. Local fracturing at minor fault intersections may have been the most important locus for the initial channelways. Once the fluids from an individual chamber reached the near-surface area, a trunk channel resulted along the zone of maximum pressure gradient.

4. There is no positive evidence to support explosive action at the elevation of exposure of the pipes. The non-rotational aspect of Zone II and the absence of Zone III in some pipes suggest that explosive action was not important. There is no definite proof in Zone III as to whether the fragments moved up or down; however the occurrence of quartz monzonite fragments in the Copper Hill pipe suggests one period of upward movement (Section Fig. 3).

5. Early fluids moving up trunk channels penetrated the adjoining wall along existing joint and fracture surfaces. Some of the fluids replaced the rock adjacent to the joint and fracture surfaces with quartz and orthoclase and formed a partially cemented and partially replaced breccia.

6. The fluid in the more open trunk channels removed much material and left open spaces in the interstices separating fragments. The fragments in these trunk channels were rounded, rotated, and mixed together. The process by which the material was removed is open to question. It is suggested that incipient alteration of the fragments loosened the mineral grains along the borders. This loosening effect was accentuated by contemporaneous movement and attrition of the fragments. The through-going fluids removed the finely ground material.

7. In the later part of this stage of development, as overall pressures decreased, most of the movement of the fragmental mass may have been downward as the whole pipe slumped from continual removal of the fine abraded material. Zone III continued to work outward from the trunk channel into Zone II. After the pipe was well developed, portions of Zone II probably tended to slump in toward Zone III; thus forming more open space in the Zone II.

8. Following the formation of the open mass of "crackle" breccia and "boulder" breccia in Zones II and III, quartz was deposited in the open interfragment spaces as well as in available joints and fissures. During and after deposition of quartz, structural adjustment, by renewed movement on regional faults or general flexures caused by movements in the underlying magma chamber, fractured some of the early cementing and replacement minerals. Then sulfides were deposited in these fractures, showing a strong preference for those in quartz.

9. Faulting and fracturing continued after the sulfide stage, and portions of several pipes have been displaced as much as 200 feet.

ORE PIPES VERSUS BARREN PIPES

An interesting and somewhat perplexing problem in the study of mineralized pipe areas or districts is why some pipes are ore-bearing and some are not. Joralemon (12) has discussed this problem in relation to the

Copper Creek district, Arizona, where only a few out of dozens of pipes contain ore bodies.

In Copper Basin some pipes among those tested are known to be ore-bearing whereas some are known to be essentially barren and could be called "alteration" pipes. It appears that a critical factor in ore deposition in the Copper Basin pipes was a period of structural deformation that followed the formation of the pipes and the clogging of the pipes by quartz replacement and cementing material. The sulfide minerals were deposited largely in the fractured, relatively brittle, inter-fragment or vein quartz, and when this quartz was not fractured prior to or during this sulfide stage, the pipe remained as an "alteration" pipe, largely devoid of ore minerals. Movement along faults striking N 10–30° W and N 10–30° E appear to have been important in keeping critical channelways open and in fracturing the various types of quartz in the ore-bearing pipes. Higher grade lenses within the ore-bearing pipes appear related to these faults. Where silicification has been intense the post-quartz deformation may be effective only on the outer edges of the pipe leaving a barren central plug. It is thought the strongly mineralized pipes resulted from the combination of (1) the deep-seated structure that localized the breccia pipe and could potentially reopen as a through-going ore fluid channel, and (2) the presence of fractured quartz, a relatively permeable host rock in the pipes.

RELATION OF MINERALIZED BRECCIA PIPES TO PORPHYRY COPPER DEPOSITS

The geological environment in Copper Basin is strikingly similar in many respects to that of the typical porphyry copper deposit in the Southwest and especially to the nearby deposit at Bagdad. The composite Copper Basin stock including equigranular quartz monzonite, quartz monzonite porphyry, and finer grained dike equivalents, is similar to rock sequences in many of the porphyry copper deposits. The hypogene sulfide mineralization, generally classified as mesothermal in porphyry copper deposits, consists essentially of pyrite, chalcopyrite, and molybdenite at Copper Basin. The hydrothermal alteration is not as intense as in some porphyry copper deposits but is similar in composition. Spectrographic analyses of fresh and altered quartz monzonite suggest that alteration has removed sodium, calcium and magnesium and has increased the potassium content.

The fracture patterns in Zones I and II (Fig. 5) are common to the porphyry copper deposits. The present top of the water table roughly coincides with the floor of Copper Basin and the oxidation zone is largely restricted to the upper portions of pipes represented by the conical hills. Exploration to date indicates that the primary mineralization in the inter-pipe (Zone I) areas everywhere contains an appreciable copper content.

The literature does not indicate a common association of mineralized pipes with porphyry copper deposits in the southwestern United States, although Anderson and others (3, p. 75) observed mineralized breccia pipes near the Bagdad deposit and Walker and Walker (22, p. 152) describe a breccia pipe adjacent to the Sacramento Hill stock at Bisbee, Arizona. In

South America there appears to be a closer relationship of pipes to some porphyry copper deposits and Richards and Courtright (21) describe a large central breccia pipe surrounded by smaller satellitic pipes as important features of the Toquepala, Peru, porphyry copper deposit.

It is suggested that erosion in Copper Basin may have revealed the lower portion of a porphyry copper deposit and that the pipes served as main conduits or channelways for the ore depositing solutions. Pipes serving as the main channelways for the ore depositing solutions within a restricted orifice or root portion of a composite stock, as in Copper Basin, may be a plausible explanation as to why some porphyry copper deposits are restricted to a certain part, in plan, of the associated stock rocks as observed at or near the surface.

ORE DEPOSITS

The ore deposits of the Copper Basin district have been tentatively divided on the basis of their relationship to the three groups of rocks of known or assumed age. The proposed age classification used is (1) Precambrian, (2) Laramide (?) and (3) late Tertiary (?) and Quaternary.

Precambrian deposits have yielded minor gold and copper ores associated with tourmaline-quartz veins.

Laramide (?) deposits, which have yielded the bulk of the district production, include copper and molybdenum associated with pipes, and zinc-lead-silver fissure-filling and replacement veins.

Late Tertiary (?) and Quaternary deposits include mercury prospects associated with rhyolite and gold placers.

The early history is obscure but the Copper Basin district was officially recognized about 1890. Gold seekers had undoubtedly been in the area long before this date. Production has been mainly from direct shipping siliceous copper fluxing ores. Three main periods of activity were 1914 to 1919, 1942 to 1950, and 1955 to the present time. Most of this copper production has come from the Commercial mine owned by Phelps Dodge Corporation. Small shipments of zinc, lead, silver and gold have been made from numerous mines and prospects, but largely from the U. S. Navy and Boston-Arizona mines. Sporadic gold placer operations have been carried on since the discovery of the district.

Precambrian Deposits.—Precambrian tourmaline-quartz veins containing small, irregular ore shoots of gold and copper ore have been exploited largely in the western part of the district. Coarsely crystalline, milky to glassy, quartz veins, locally containing black tourmaline and brown carbonate, fill two main fissure systems striking N 60°–75° W, and N 55°–70° E. Sulfide minerals include pyrite, chalcopyrite and minor dark brown sphalerite. Gold appears closely associated with dark bronze colored, cubic pyrite or the oxidized gossan derivative. Oxidation has rarely extended to more than 50 feet below the surface. The massive pyrite portions of the veins have been oxidized to cellular and massive, varnish-type gossans.

Laramide (?) Deposits.—The bulk of production from the district has been from disseminated copper-molybdenum mineralization above the pre-

sumed root of the composite stock, but a rough zonal arrangement of metals characteristic of porphyry copper deposits is present in Copper Basin. This consists of the central, disseminated copper-molybdenum zone surrounded by vein-type zinc-lead-silver deposits.

Most of the lead-zinc-silver deposits are concentrated along either a north trending high-angle fault, or the Navy thrust fault on the west side of Copper Basin. The Boston-Arizona mine, approximately two miles northwest of the composite stock, has been shown by Johnston (13, p. 112) to be clearly related in space and time to a quartz latite porphyry dike that radiates out from the composite stock.

Disseminated copper-molybdenum mineralization is distributed throughout an area of approximately one-half square mile (Zone I as described under the Section on Mineralized Breccia Pipes). Most known ore bodies in this area consist of mineralization in pipes, but ore also occurs in bodies peripheral to pipes and as mineralization in shear zones. In several ore bodies the ore mineralization was to some extent controlled by N 10°–30° E and N 10°–30° W faults. Higher grade lenses and poorly defined "veins" within the ore bodies are oriented by these structures suggesting that they were open during the main period of ore deposition.

Each mineralized pipe is the center of an aureole of alteration. The aureoles have different diameters depending on the intensity of hydrothermal activity, and where pipes are closely spaced they overlap, producing a complex alteration pattern. Mineralization differs in grade between ore bodies —both as to copper content and copper-molybdenum ratio. Ore reserves published for the Ranwick, Inc. ground in 1957 (20) listed 4,000,000 tons averaging 0.913% Cu and 0.124 MoS_2.

Both supergene and hypogene ore bodies are present in Copper Basin. An example of the former is the Copper Hill mine where drilling has disclosed a supergene enriched blanket about 80 feet thick in which the primary copper grade has been approximately doubled by the addition of chalcocite, copper carbonate, oxide minerals, and native copper. Interestingly enough, the Copper Hill ore body also contains a zone of secondary enrichment of molybdenum which occurs just above, and in the upper part of the zone of copper enrichment. The secondary molybdenum mineral is ferrimolybdite, a bright yellow oxide. Some ore bodies such as the Loma Prieta do not have a significant zone of secondary enrichment. Secondary enrichment is controlled by (1) the top of the water table, which stands approximately at the general floor elevation of Copper Basin, and (2) the association of most of the ore with quartz that resists the weathering processes except where fractured by post-ore deformation.

At several localities in Copper Basin, deposits of terrace gravels have been cemented by copper carbonate and oxide minerals. The largest of these is probably the Aztec deposit at the north end of the Smelter Hill pipe, but deposits also occur at the south end of Smelter Hill and in the bottom of Copper Basin wash east of the Aztec workings. Apparently the oxidation of pyrite produced ferrous sulfate and sulfuric acid, which dissolved copper. Copper in solution emerged from the side of Smelter Hill

and followed down the bedrock surface until a change in PH caused precipitation of the copper in the lower few feet of gravel. Copper minerals form coatings on detrital grains ranging in size from fine grained sand to boulders three feet in diameter.

Magnetic and Soil Sampling Data.—Vertical intensity magnetometer surveys in Copper Basin were conducted in an effort to locate negative magnetic anomalies. These, in theory, may represent areas in which hydrothermal alteration has been intense and the original magnetite of the intrusive host rock has been altered to iron minerals such as limonite and pyrite with relatively low magnetic susceptibilities.

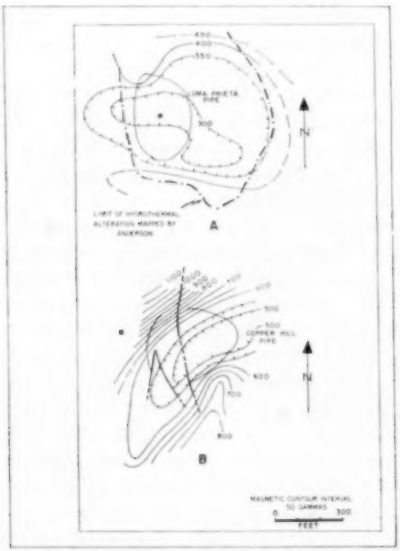

FIG. 7. Negative magnetic anomalies centered on Loma Prieta and Copper Hill breccia pipes. These anomalies are related to hydrothermal alteration which has spread outward from the pipes. Areas within circles are altered rock.

Figure 7 shows magnetometer contour lines in relation to the Loma Prieta and Copper Hill pipes. In these areas the anomaly location corresponded closely to observable strong hydrothermal alteration. In some localities no anomaly was found over mineralized pipes—this probably is due to the fact that aureoles of alteration from adjacent pipes had overlapped, leaving no unaltered rock between.

Samples were collected corresponding to (1) intense alteration and minimum magnetic susceptibility, (2) medium alteration and medium magnetic susceptibility, and (3) fresh rock with high magnetic susceptibility. Thin sections and spectrographic analyses of these samples indicate that the conversion of magnetite to limonite and pyrite increased progressively with

sericitization of plagioclase, kaolinization of potassium feldspar, and chloritization of mafic minerals. It has been concluded that the method, under favorable circumstances, can be used for the location of covered pipes or altered zones in Copper Basin.

Limited soil sampling was done in leached outcrops of mineralized pipes in an effort to establish prospecting guides to ore. Analyses were made of copper and molybdenum content, and by comparison with drill hole information it was found that the soil content of copper was erratic and bore no relationship to underlying primary mineralization, but that the soil content of molybdenum was approximately equal to that of the primary ore body. The usefulness of this relationship is limited by the unpredictable ratio of copper to molybdenum in the primary ore bodies of the district.

Late Tertiary (?) and Quaternary Deposits.—Small amounts of cinnabar, associated with pyrite, hematite, and limonite, have been found in and near rhyolite and rhyolite breccia dikes in the southwest corner of the district. No mercury production has been reported from lode deposits but natural amalgam has been reported in gold placers from streams that drain the area.

Wilson (24) has described the Copper Basin gold placer deposits in some detail. The only active record period of activity was from 1929 to 1937. The source of the gold, especially the coarser nuggets, was undoubtedly the Precambrian tourmaline-quartz veins.

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BERYLLIUM-BEARING TUFF IN THE THOMAS RANGE, JUAB COUNTY, UTAH[1]

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CONTENTS

	PAGE
Abstract	941
Introduction	941
Geology	942
Volcanic rocks	942
Structure	943
Mineral deposits	943
Composition of the ores	946
Origin of the deposits	948
Potentialities of the district	949
References	950

ABSTRACT

Recently discovered beryllium deposits in the Thomas Range, Utah, are along the periphery of the fluorspar district at Spor Mountain. The beryllium is in altered rhyolite tuff of Tertiary age and is associated with genetically related fluorite, quartz, chalcedony, opal, calcite, and montmorillonite and with residual quartz, feldspar, and biotite. Nodules of silica and fluorite contain more beryllium than the enclosing tuff. The ores probably were formed by fluorine-rich solutions derived from rhyolitic magma related to a second period of volcanic activity.

The district promises to be an important source of beryllium.

INTRODUCTION

THE discovery of beryllium in tuffs near Spor Mountain in the Thomas Range, Utah, has attracted wide hope that a major source of beryllium may be developed there. The district was visited by the authors in June 1960 after preliminary studies of ore samples. Appreciation is extended for the hospitality shown by the Vitro Minerals Corp., Beryllium Resources, Inc., and The Combined Metals Reduction Corp., who are most active in exploring the deposits, and also by the Spor brothers who hold many claims in the district. Eugene Hotchkiss and C. C. Woo of Vitro Minerals Corp., and Page T. Jenkins, of Casper, Wyoming, kindly supplied the samples used in the preliminary studies.

The area, commonly called the Topaz district, is at Spor Mountain, in the southwestern part of the Thomas Range and is 46 miles northwest of Delta, the nearest town. The beryllium deposits known in June were in

[1] Publication authorized by the Director, U. S. Geological Survey.

secs. 5, 8, and 9, T. 13S., R. 12W., and in the unsurveyed sections directly north of sections 2 and 5 of that township.

The district was first developed as a source of metallurgical fluorspar, the first shipments being made in 1943. The fluorspar was found to be radioactive, a feature that lead to a detailed study of the district in 1951 and 1952 as a potential source of uranium (3). Eventually an important uranium mine was developed about a mile east of Spor Mountain.

The high concentration of beryllium in some of the tuff was independently recognized in December 1959 and January 1960 by Beryllium Resources, Inc., and Vitro Minerals Corp., respectively. Intensive exploration began in April 1960 and in June two drills were in operation. Because of the peculiar nature of the ore, and its similarity in appearance to barren tuff, all major companies exploring in the area were controlling their exploration by beryllium determinations made with nuclear devices (1).

GEOLOGIC FORMATIONS

Spor Mountain is composed of sedimentary rocks of Paleozoic age that are intruded by small dikes and plugs of rhyodacite and rhyolite; volcanic explosion pipes filled with breccia are common along its eastern side. The Paleozoic rocks range in age from Early Ordovician to Devonian and appear to be in a conformable sequence consisting of the Garden City formation (mostly limestone), Swan Peak formation (lower part shale; upper part quartzite), and Fish Haven dolomite, all of Ordovician age; the Florida dolomite of Ordovician or Silurian age; the Bell Hill dolomite, Harrisite dolomite, Lost Sheep dolomite, and Thursday dolomite, all of Silurian age, and the Sevy dolomite and the equivalent of the Simonson dolomite and the Guilmette formation (dolomite and limestone) of Devonian age.

The sedimentary rocks are overlain by volcanic rocks of Tertiary age, and all the Tertiary and older units below 5,200 feet are partly covered by Lake Bonneville beds of Pleistocene age. Spor Mountain itself is a large ridge that is completely surrounded by Lake Bonneville deposits, through which many smaller hills also rise, forming low foothills alongside the mountain. Most of the beryllium-bearing tuff is covered by these Lake Bonneville beds. Inasmuch as the volcanic rocks are hosts of the beryllium deposits, they are described in more detail below.

Volcanic Rocks.—The volcanic rocks of the Thomas Range consist of flows, tuffs, breccias, and small intrusives, which range in composition from augite-enstatite rhyodacite to rhyolite. The rhyolite and rhyolite tuff that are of current economic interest are parts of two volcanic sequences; the older rocks are of probable Miocene age, the younger of probable Pliocene age.

Along the west side of Spor Mountain, rocks of the younger sequence consist of tuff, overlain by rhyolite. The tuff is largely a poorly bedded, gray, rather soft, altered rock, 200 to 300 feet thick. Phenocrysts of smoky quartz, in bipyramids, and crystals of sanidine and biotite, all 2 mm or less in long dimension, are embedded in a structureless dull light-gray to white matrix

that presumably is altered ash. Semiquantitative chemical determinations on 18 samples show that the calcite content of this altered tuff ranges from less than one to nearly 50 percent. The calcite content is not closely related to the beryllium content.

Bedding is inconspicuous in much of the tuff, and only a few lenticular beds contain pebbles or cobbles of rhyolite or other rocks.

The older rhyolite is porphyritic, with phenocrysts of sanidine, biotite, plagioclase, and quartz 1/50 to 1/10 inch across set in a partly devitrified glassy groundmass.

The tuffs of the younger sequence are chiefly white or pale greenish-white friable, vitric tuffs. Most layers contain pumice fragments ranging from 1/10 to 1 inch in size. Crystal fragments are also present and consist mainly of quartz and sanidine. These two minerals may make up about 10 percent of the tuffs, but they are rarely recognizable in hand specimen. The matrix of the tuff is a compact ash.

The younger tuffs can be distinguished from the older tuffs because (1) they contain abundant pumice fragments that are rare in the older tuff, (2) they are vitric tuffs, whereas the older are crystal tuffs, and (3) the younger tuffs are more porous than the older.

The rhyolite of the younger sequence is gray to white and contains phenocrysts of quartz, sanidine, plagioclase, and biotite set in a mosaic of quartz and feldspar anhedra less than 0.1 mm in diameter. Some rocks have a glassy groundmass. Topaz subhedra less than 0.1 mm long are rare, and, in a few places, fluorite and garnet are also found. The rhyolite contains lithophysae as much as 4 inches in diameter. In places crystals of topaz, specular hematite, and rarely, crystals of pink beryl, garnet, or of bixbyite occur in the rhyolite. The beryllium contents of seven samples of this rhyolite range in value from 4 to 14 ppm, averaging 7 ppm (4). This average is somewhat higher than that of most rhyolites.

STRUCTURE

The Paleozoic sedimentary rocks and the older sequence of volcanic rocks strike northeast and dip northwest; the younger volcanic sequence, however, shows but little tilting. An immense number of faults of five general types cut the Paleozoic rocks. These are (1) small northeast-trending thrust faults, (2) northeast-trending normal and reverse faults with moderate dip, (3) northwest-trending faults, mostly high angle, (4) north-trending faults, and (5) east-trending faults. Rocks of the older volcanic sequence are cut by some of the northeast-trending normal and reverse faults, north-trending faults, and east-trending faults. Rocks of the younger sequence are cut by only a few faults and the movement on these was small.

MINERAL DEPOSITS

Fluorspar deposits occur in a north-south belt down the middle of Spor Mountain, whereas the known beryllium deposits are low on the eastern and western flanks of the mountain. Thus, fluorite-rich deposits are in the

center of the district and beryllium-rich but fluorite-poor deposits are at the periphery (Fig. 1). Staatz and Osterwald (3, p. 46) have classified the fluorspar deposits as: (1) pipelike bodies, (2) veins, and (3) disseminated deposits. The disseminated deposits are the only ones known to contain much beryllium.

The pipelike bodies are the most important fluorspar deposits in the district, and at least 99 percent of the total production comes from ore bodies of this type.

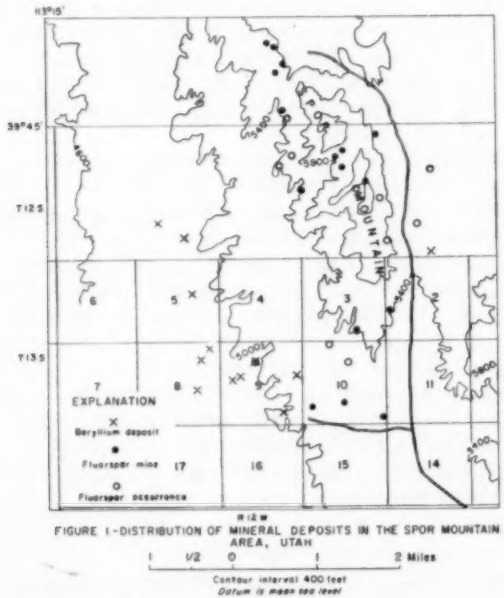

FIG. 1. Distribution of mineral deposits in the Spor Mountain area, Utah.

The pipelike deposits range from less than a foot in diameter to 155 feet long by 106 feet wide. Most plunge 52 to 90 degrees to the east. They are mainly in dolomite, although a few are partly in intrusive breccia. The pipes generally are found along or adjacent to faults or adjacent to intrusive breccia masses.

Veins are common but most are small and only three of them have been sources of fluorspar. Most of them range in width from a fraction of an inch to 14 feet and in length from a few inches to 40 feet, although one has been traced for 220 feet. They thicken and thin abruptly with depth. Veins cut most of the formations on Spor Mountain and may strike in any direction and are steep. Veins, like the pipes, are generally along or near faults or near intrusive breccia bodies.

Disseminated deposits of fluorspar are along the south and west sides of Spor Mountain. They have not been mined because the fluorite content does not exceed 20 percent, but they are the only known fluorspar deposits to contain concentrations of beryllium minerals.

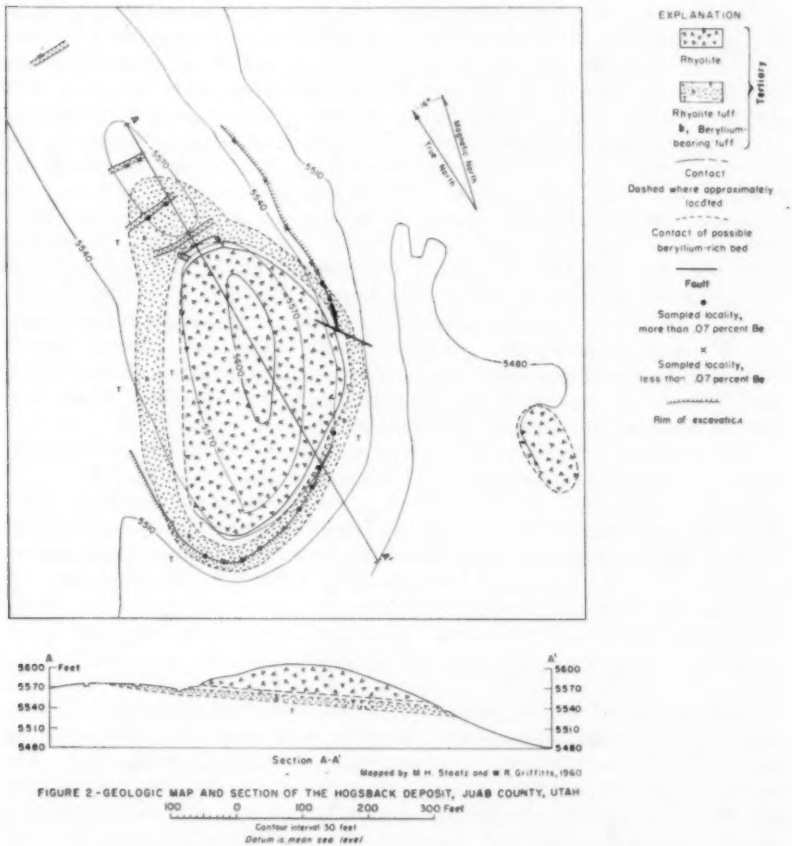

FIGURE 2.-GEOLOGIC MAP AND SECTION OF THE HOGSBACK DEPOSIT, JUAB COUNTY, UTAH

FIG. 2. Geologic map and section of the Hogsback deposit.

These disseminated fluorspar deposits are in rhyodacite, rhyolite, and tuff. The distribution of fluorite is irregular; it may constitute 20 percent of the rock in one place and only a fraction of a percent a few feet away. The richest and most extensive deposits of this type are in the more porous tuff where fine-grained fluorite has replaced clay-rich layers.

So far beryllium has been found in important concentrations only in disseminated deposits in the rhyolite tuff in which it is associated with

moderately small amounts of fluorite. The fluorite-rich pipes and veins and fluorite-free tuff apparently contain little beryllium. Within the tuff unit, beryllium-rich layers may be 20 feet thick or they may be less than 2 feet thick. The length of these layers along strike and down dip is unknown but some have been traced for at least 200 feet. Figure 2 shows, rather optimistically, an erosional remnant of a beryllium-bearing layer at the Hogsback deposit to extend for over 550 feet. The original extent is, of course, unknown. In the Hogsback area the tuff of Miocene age is exposed over an area about 900 feet long and 400 feet wide and is at least 100 feet thick. It is a friable quartz-sanidine tuff which contains near its top several layers of volcanic breccia with pieces of porphyritic rhyolite up to several feet across. The beryllium-bearing tuff at the Hogsback deposit, is, in places, pink or light red and may also contain black spots or moderately widely dispersed areas of manganese oxides. This is also a feature of the tuff in outcrops west of the mountain. Neither the pinkish color nor the spots are particularly widespread outside of the mineralized zones, but not all rocks showing these features are rich in beryllium. The beryllium-rich zone, in tuff and breccia, reaches a thickness of 6 feet on the east side of the ridge and may be thicker at the south end. Sixteen samples were collected from this 6-foot zone; fifteen contained from 0.07 to .75 percent Be and one contained less than 0.07 percent. Siliceous and fluoritic nodules picked from the tuff contain higher concentrations.

The position of beryllium-rich layers in the tuff unit differs from place to place. At the Hogsback deposit, at the Rainbow No. 2 claim (NW ¼ sec. 9) (Fig. 1), and in the south-central part of sec 8 the known beryllium layers are in the upper part of the tuff; on the Roadside claim (NE ¼ sec. 8) some of the beryllium layers are near the middle, and in the Blue Chalk deposit (SE ¼ sec. 9), beryllium may be at the base of the tuff. In places the tuff contains more than one beryllium-rich layer.

COMPOSITION OF THE ORES

Minerals found in the fluorspar deposits are fluorite, montmorillonite, quartz, opal, chalcedony, calcite, dolomite, and carnotite. All of these except dolomite and carnotite have been found in the beryllium deposits. The beryllium deposits contain in addition sanidine, biotite, bertrandite, and gypsum. The sanidine, biotite and part of the quartz are merely residual minerals from the original tuff, the other minerals were introduced. Gypsum forms thin veinlets in the tuff near the surface. All the minerals are so very fine-grained that they are difficult to identify microscopically.

Nodules of fluorite, silica minerals, and, less commonly, calcite are embedded in the altered tuff. They range in length from 1/10 inch to at least a foot. The color of the nodules ranges from white or gray to dark purple reflecting an increase in fluorite content. The color is uneven and either the core or the rind of a nodule may be lightest; light rinds may be more common than dark rinds in beryllium-bearing nodules. Purple fluorite that accounts for the purple color of many nodules may occur in several forms:

as tiny particles disseminated through the silica, as tabular masses about 1/100 inch thick, and 1/10 to 1/4 inch across, or as aggregates of 1/16 to 1/8 inch grains. The silica minerals include quartz, chalcedony, and opal, which locally impregnate the tuff as well as form nodules in it. Grains of quartz and of calcite in the nodules are about 1/10,000 inch in diameter. Thin-section study suggests that the history of mineralization may be complex in spite of the simple mineralogic composition. One nodule showed that early very fine-grained dusty-appearing quartz was cut by chalcedony, which in turn was cut by fluorite-bearing and moderately coarse-grained quartz; other nodules contain dendritic masses of purple quartz. The beryllium content of five nodules was found to be 7 to 22 times that of the enclosing tuff, as shown below.

Sample	1	2	3	4	5
Percent Be in nodule	3.8	.63	3.0	1.8	3.2
Percent Be in tuff	.54	.08	.17	.08	.38

Some silica nodules from barren layers of tuff contain very little beryllium, and calcite nodules seem generally to be barren.

Bertrandite ($2Be_2SiO_4 \cdot H_2O$) is the only beryllium mineral positively identified in the district. Lines characteristic of bertrandite can be found in X-ray diffraction patterns of material that contains 3/4 percent or more of Be. Evidence of bertrandite cannot be found in the diffraction patterns of samples containing less than about 3/4 percent Be because the strongest bertrandite line coincides with a line from fluorite, which is always present. The unusual environment in which the beryllium deposits were formed, perhaps at a low and varied temperature, suggests that they may contain amorphous bertrandite (gelbertrandite of Semenov (*2*)), sphaerobertrandite (*2*), or even new beryllium minerals that have not been found elsewhere. Nearly all the beryllium is readily soluble in H_2SO_4 or HCl. This may result from the fine state of division of bertrandite, which is normally slowly attacked by these acids, or from the presence of amorphous or crystalline minerals more soluble than bertrandite.

Four nodules that contain more than 1 percent Be were analyzed spectrographically for other elements, with the results shown in Table 1. Inasmuch as the nodules contain only a small amount of residual tuff, most of the elements in them must have been carried to their site of deposition by the mineralizing solutions. The high concentrations in the manganiferous nodule (H29a), when compared to the other nodules, of tungsten, thallium, barium, strontium, lithium, vanadium, lanthanum, neodymium, copper, lead, and molybdenum are conspicuous. However, the low concentrations in all nodules of the common ore metals, copper, lead, zinc, cobalt, and nickel are also striking. This poverty of common metals is found in several other nonpegmatitic beryllium deposits.

TABLE 1

SPECTROGRAPHIC ANALYSES OF BERYLLIUM-BEARING NODULES

Element	Field number			
	H22b	H29a	Rb	Rb6
	Laboratory number			
	282353	282354	282355	282356
Fe	700	1,500	1,500	700
Mg	3,000	3,000	3,000	3,000
Ca	M	M	M	M
Na	1,500	3,000	3,000	3,000
K	<7,000	<7,000	<7,000	<7,000
Ti	15	300	150	150
P	<2,000	<2,000	<2,000	<2,000
Mn	150	70,000	150	70
Ag	<1	<1	<1	<1
Au	<20	<20	<20	<20
B	300	700	700	150
Ba	7	150	1.5	Tr
Bi	150	70	15	<10
Cd	<50	<50	<50	<50
Co	7	<5	<5	<5
Cr	1.5	1.5	7	3
Cu	Tr	7	Tr	Tr
Ga	<2	1.5	1.5	Tr
Ge	<10	<10	<10	<10
La	70	300	30	700
Li	Tr	700	300	<200
Mo	15	30	<5	<5
Nb	30	50	15	<10
Nd	<100	300	<100	<100
Ni	<3	15	70	<3
Pb	70	150	15	Tr
Sn	70	<10	<10	<10
Sr	70	1,500	30	70
Th	<200	<200	<200	<200
Tl	<100	300	<100	<100
U	1,500	700	700	700
V	<10	15	<10	<10
W	<100	300	<100	<100
Y	150	300	300	150
Yb	15	30	30	15
Zn	<200	<200	<200	700
Zr	Tr	30	30	15

Values in parts per million. R. G. Havens, analyst. Semiquantitative analysis in which values are reported to the closest number in the series 1.5, 3, 5, and 7. M means the element is a major component, Tr means trace. H22b—fluoritic nodule, Hogsback deposit; H29a—black-stained nodule, Hogsback deposit; Rb—fluoritic nodule, Rainbow No. 2 deposit; Rb-6—zoned fluoritic nodule, Rainbow No. 2 deposit.

ORIGIN OF THE DEPOSITS

The problem of origin of the deposits involves (1) a source of mineralizing solutions carrying Be, F, Mn, Fe, and smaller amounts of other elements, (2) a means by which the solutions can be taken to and introduced into the

host rock, and (3) a mechanism by which the transported materials can be deposited from the solution.

The deposition of beryl, topaz, and bixbyite in cavities in rhyolite flows indicated that Be, F, Mn, and Fe were present in mobile solutions after the rhyolite was largely solid. Inasmuch as beryllium, manganese, and iron form readily soluble simple or complex fluorides their association with fluorine minerals both in the rhyolite and in the beryllium deposits suggests that they were carried in solution as fluorides. It is likely that not all the rhyolite magma of Pliocene age reached the surface, so we may postulate the presence of metal-bearing fluoride solutions after the consolidation of a covered mass of such magma. Thus the Pliocene rhyolite magma is a plausible source of metal-bearing solutions. It is interesting to note that the rhyolite averages about 7 parts per million of beryllium, which is only slightly higher than other rhyolites, which average about 5 parts per million. Hence this rhyolite magma probably was not unusually rich in the element. The mineralizing fluids would escape through all permeable zones, among which must have been the persistent faults that are in or near the bodies of mineralized tuff. Being persistent, they may have served in places as the main channels.

Deposition of the metals from the solution would require the dissociation of the complex fluoride ions. This can be brought about by reducing the fluoride ion concentration in the solution, as by the formation of fluorite through reaction between the solution and limestone or dolomite. Where the fluoride ion concentration was maintained at a high level, as along major conduits or channels, large amounts of fluorite could be deposited but few other elements would leave the solution. Precipitation of fluorite from nearly spent solutions farther from the source or from main conduits would induce nearly simultaneous breaking up of the fluoride complexes of Si, Be, Fe, Mn, and U, and minerals of these elements would be deposited along with fluorite. Permeable calcareous rocks, such as are found in the tuff, therefore would be favorable host rocks.

POTENTIALITIES OF THE DISTRICT

At present it seems clear that beryllium is widely distributed, that some beryllium-bearing tuff beds persist at least for several hundred feet, and that many beds average one or two tenths of a percent Be. Also the district may contain several hundred thousand tons of potential ore, much of it in bodies of minable size.

The unusual ore will require hitherto unused methods of mining and processing and therefore they must be evaluated somewhat differently from other beryllium ores. The low grade, one or two tenths percent, of beryllium suggests that the ore should be beneficiated before the beryllium is extracted. Unfortunately, we have been unable to concentrate the beryllium from the ore by any physical method because the extremely small beryllium-rich particles are embedded in most of the newly formed minerals. The solubility of the beryllium in sulfuric acid shows that hydrometallurgical

methods may be used, with possible production of beryllium oxide. Uranium and fluorite are potential byproducts.

U. S. GEOLOGICAL SURVEY,
DENVER, COLORADO,
Jan. 11, 1961

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A SYNGENETIC COPPER DEPOSIT OF RECENT AGE

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CONTENTS

	PAGE
Abstract	951
Introduction	951
Description	952
Vegetation	956
The copper source	956
The time factor	957
The alkalinity factor	958
Reconstruction	959
Summary	961
Acknowledgments	961
References	962

ABSTRACT

Copper deposited syngenetically in organic sediments occurs in southeastern New Brunswick, Canada, where a peat swamp contains up to ten per cent copper dry weight. This copper occurrence appears unique in that the metal is contained invisibly in subneutral to slightly alkaline peat. This contrasts sharply with the other copper swamps described in the American geological literature in which megascopic lumps and aggregates of native copper are found in organic sediments of acidic pH.

The source of the copper must be sought in the surrounding ground morainal deposits or in the underlying bedrock. The cupriferous solutions have the characteristics of deeply circulating waters, and enter the swamp as seepages. These water seepages, therefore, are not normal "outcrops" of the water table. The glaciology of the region indicates that the peat could not be more than 4,000 years old, and this maximum age is corroborated by the estimated time required to account for the emplacement of the present tonnage of metal, assuming a constant rate of copper deposition.

INTRODUCTION

THIS examination of the Tantramar copper swamp began in response to a report that a peat accumulation contained amounts of copper worthy of economic interest. The oddity of the muck was recognized at least seventy years ago when a nearby farmer, in the hope that this rich black peat would make an excellent fertilizer, attempted to induce his cucumbers to greater growth: the dose proved lethal.

The Tantramar copper swamp is located in the Tantramar Marshes about seven miles north of the town of Sackville, Westmorland County, New Brunswick. Situated at an elevation of fifty feet above sea level, it is bordered on the north and west by gently rolling hills and on the south and

east by a lowland forest. The copper swamp embraces 2½ acres, of which one acre is open and the remainder covered by a swampy forest. The bulk of the copper is contained in the forest peat, which overlies weakly mineralized sandy loam and ground morainal material. Mr. G. P. Mackay of Halifax studied the economic aspects of this cupriferous peat, and arranged limited testing with a pilot mill in an attempt to determine the most economical method of copper recovery. Some 300 tons of copper are estimated to occur in this swamp, but extraction of the metal appears too costly to warrant the financial risk involved in such a low-tonnage mining venture.

Dr. R. E. Beschel of Queen's University studied this occurrence while he was on the staff of Mount Allison University. Dr. R. H. C. Holman of the Geological Survey of Canada has also examined the Tantramar swamp. The writer is indebted to both for some data included herein.

The study of the Tantramar copper swamp yielded many perplexing problems arising chiefly from the invisibility of the copper substance. The exact form in which the metal exists is still obscure, although the type of bonding and the general nature of the copper compound is now believed to be known. This, and the cause of the copper precipitation, will be considered from experimental and theoretical viewpoints in another paper.

DESCRIPTION

The reader is referred to Figures 1 and 2 for the locations of the various features described below.[1] The swamp was visited in the autumn of 1958 and again in the following spring. Four hundred soil samples were taken along two perpendicularly intersecting lines, the sample sites being twenty feet apart in the clearing and swampy forest, and forty to eighty feet apart outside the copper anomaly in the normal forest and burnt upland. Soil specimens were collected at every foot of depth down to five feet, and were later analyzed [2] for total copper and for total organic matter (i.e. combustible material at 450 degrees C). Many pH and Eh readings were taken at various depths during the collection of samples.

The area of interest may be conveniently divided into a number of sectors, as follows:

Copper Swamp

The copper swamp consists of two parts, the clearing and the swampy forest.

Clearing.—The clearing, elongate east–west, is practically devoid of vegetation, and anomalous copper content is present down to the depth tested (i.e. five feet). Two materials are dominant (a) sandy loam, (b) forest peat.

The clearing is largely blanketed by a sandy loam. Blocks and boulders of gritty gray-green sandstone, some of them showing pitting, are scattered

[1] The sketch map was drawn from a plan provided by Holman; the cross-section was constructed from a plane table survey along the sample lines.

[2] Throughout this paper, copper and organic matter percentages refer to soil dry weight.

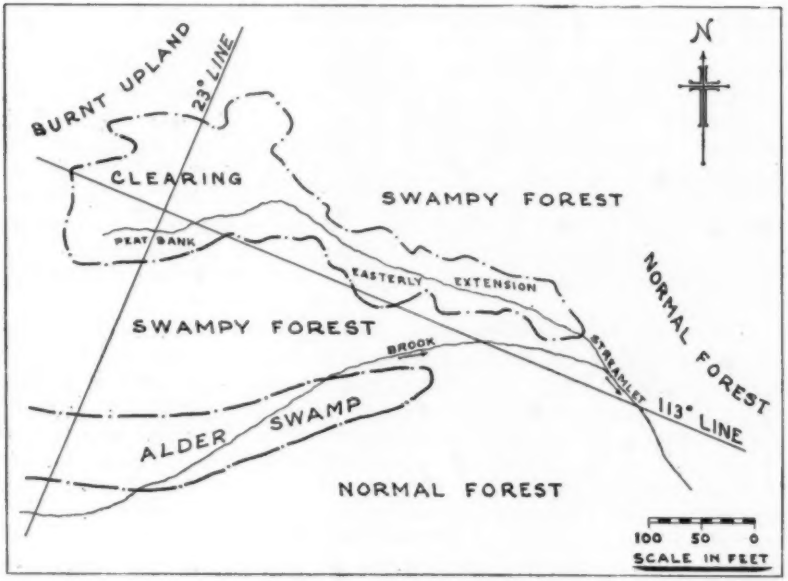

FIG. 1. Sketch map of area.

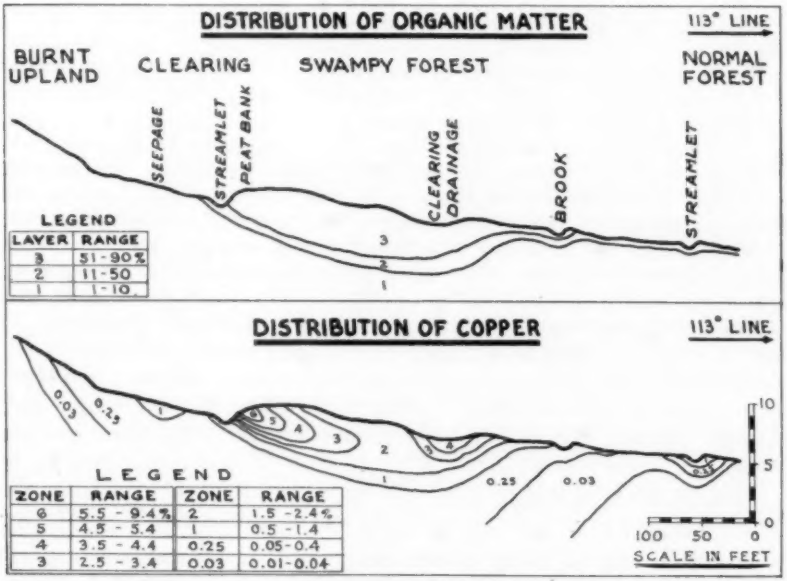

FIG. 2. Cross section of area.

about on the surface. Malachite stains are present on a few boulders, and some fragments of wood are also coated with malachite films. The sandy loam generally contains less than 10 percent organic matter and less than one percent copper. At a few feet of depth, ground morainal material occurs containing about one percent organic matter and 0.1 percent copper. The maximum metal concentrations occur in isolated "pockets" surrounding individual seepages of water. These seepages, which are apparently restricted to the clearing, are especially noted for the flourishing moss *Pohlia nutans* which Beschel (1) found to contain up to 3.8 percent copper; this represents a threefold concentration of the metal relative to the underlying soil. The pH of the sandy loam varies from 5.5 to 6.5, and the Eh from 0.14 to 0.29 volts.[3]

The second material, forest peat, occurs in a peat bank parallel to the southern margin of the clearing. It averages twenty-five feet in width and overlies the sandy loam. The "forest" peat, about two feet thick, is a black mucky material containing 60 to 80 percent organic matter and 3 to 10 percent copper. It consists of many particles cemented together by a brownish earthy material having the appearance of limonite. Quartz, present as small irregular grains, was the only mineral positively identified by the writer. After a long dry spell one summer, a bluish coloration (azurite?) was reported on the surface of the peat, the pH then being 8.1 (1). In the spring and fall, when the writer visited the swamp, this bluish hue was absent; the pH then varied from 6.0 to 7.2 and the Eh from 0.08 to 0.23 volts. As in many soils, capillary action and the removal of underground water by the growth of frost crystals is a feature of the peat bank in the late fall and winter.

In the easterly extension of the clearing, four feet of black peat containing 3 to 6 percent copper overlie a thin layer of clay and ground morainal material having less than one per cent copper.

Swampy Forest.—The swampy forest is a continuation of the peat bank, to the south, and is covered with vegetation, mainly evergreens; the swampy forest also includes the area northeast of the clearing. Black peat is the dominant material of this sector, extending to a depth of over three feet. It overlies an inch or so of blue clay, a few inches of coarse pink sand and, finally, the glacial deposit. This forest peat is somewhat more fibrous than that of the bare peat bank, and is overlain by a few inches of humus that supports the growth of a wide variety of plants. Although the humus contains only 0.03 to 1.0 percent copper (1), the peat at just four inches depth has 2 to 3 percent. Copper content in the swampy forest reaches a maximum of 5 percent at two and three feet of depth. Laterally, the copper percentages diminish, in a southerly direction, to less than 0.01 percent towards the margin of the normal forest. The pH of the humus varies from 4.2 to 5.1 and the Eh from 0.21 to 0.29 volts, while the pH of the peat below the influence of the trees ranges from 6.0 to 7.0 and the Eh from 0.06 to 0.20 volts.

[3] It is to be noted that the pH and Eh readings recorded herein were taken in the fall and spring, and thus may not be indicative of the conditions prevalent during other seasons.

Alder Swamp

The alder swamp, smelling slightly of hydrogen sulfide, lies 200 feet south of the clearing and extends east–west for about 500 feet, averaging 60 feet wide. It divides the swampy forest from the normal forest, and is the only sector in which the oxidation potential is negative. The copper content decreases rapidly on entering this sector, dropping to less than 0.1 percent in the upper one or two feet of sedge peat. The underlying clay, sand, and ground morainal material contain as much as 0.6 percent copper, but this decreases again to less than 0.1 percent at only four feet of depth. The pH of the sedge peat varies from 5.1 to 5.9 and the Eh from −0.03 to −0.21 volts.

Burnt Upland

The burnt upland borders the north and west of the clearing and, as can be seen from the cross-section, the copper content drops sharply to less than 0.01 percent. The elevation rises rapidly with a slope of 500 feet per mile; consequently, this sector is not swampy. The upland was burned over in 1955. The pH of the soil varies from 3.6 to 5.2 and the Eh from 0.20 to 0.34 volts.

Normal Forest

This sector occupies the southern and eastern extremities of the map area, and is considerably drier than the swampy forest, although not necessarily higher in elevation. Contained copper is below the detectible limit of the assay method (i.e. below 0.01 percent). Vegetation is dense, being composed of the red spruce-balsam fir assemblage typical of many evergreen sections of New Brunswick. The pH of the soil varies from 4.0 to 5.4 and the Eh from 0.21 to 0.32 volts.

The Cross-Section.—A study of the Tantramar cross-section reveals the following anomalous features:

1. The contours of copper content yield indisputable evidence for the points of entry of the cupriferous solutions: namely, the seepages of the clearing. If similar seepages existed in the swamp forest, then pockets of copper-rich material would result and should be indicated by the contours. The two seemingly anomalous pockets of higher copper content lying east of the clearing are due to the sample line fortuitously intersecting, firstly, a lobe of the easterly extension of the clearing, and, secondly, the outflowing streamlet.
2. The close association of the copper with peat is obvious.
3. The sandy loam of the clearing lies chiefly in the 0.25 percent zone. A small pocket containing 1 percent copper indicates one of the seepages from which the cupriferous solutions emerge.
4. The large quantities of copper (i.e. the 6 percent zone) occur near the surface of the bare peat bank. This is a consequence of the high soil evaporation during the summer and of the formation of frost crystals during the late fall and winter. These phenomena cause a concentration of copper in

the aqueous phase, because the metallic ions remain behind as the water is removed. A corresponding increase in the copper content of the surface peat results therefor.

5. The higher copper zones extend underground beneath the swampy forest, thereby reflecting the lower soil evaporation.

VEGETATION

The vegetation of the Tantramar area was admirably described by Beschel (1), and will not be covered herein, apart from a few points of interest to the prospector.

The scarcity of vegetation in the open part of the swamp (i.e. the clearing) results from copper toxicity; hence, a vegetal study of this sector is necessary for the detection of similar swamps in the Sackville area of New Brunswick.

Beschel's report reveals that two lichens and one moss grow in the clearing, but seedings of spruce, fir and birch, growing on the moss mat, die before reaching a height of three inches. There are two features of prime interest in this open area: (a) The moss *Pohlia nutans,* which is the dominant plant of the clearing, grows on the sandy loam and peat bank where there is no protection from copper toxicity by forest mat and/or where copper percentages are greatest. This moss suffers practically no competition from other plants and grows up to five inches in height, which is considerably larger than the normal size for this species. However, it appears etiolated and differs strikingly in its light green color from the usual dark green cushions. It is to be noted that in the swampy forest, where other plants can grow, *Pohlia* is covered and killed. The presence of *Pohlia nutans* in the swampy forest invariably indicates excessive surface copper content. (b) The lichen *Stereocaulon paschale* develops large cushions on rocks, sand, and gravel, and even on wood fragments, indicating their high degree of mineralization. *Stereocaulon* normally does not grow on wood fragments.

THE COPPER SOURCE

The source of the copper in the Tantramar swamp is not readily apparent. Geochemical measurements were made of the metal content of nearby streams, and these all gave the usual background of about 0.02 parts per million heavy metals. On the other hand, in mid-summer after a dry spell, the water issuing from the seepages contained 1.0 ppm.[4] These seepages yielded much lower assays (about 0.2 ppm) for the writer in the fall and spring, the discrepancy presumably being due to the increased runoff during that time.

Hence, the copper solutions enter the Tantramar swamp from below, emerging as seepages in the clearing. That the cupriferous solutions come up from depth is indicated by the fact that the water seepages generally do not freeze in winter, while the water of the alder swamp freezes solidly (1).

[4] Beschel, personal communication, re the results of a hydrochemical survey by Holman and Beschel.

Herein lies the explanation of the presence of copper in the swampy forest compared to the relative exclusion of it from the alder swamp, since the water of the latter appears to be a simple "outcropping" of the water table. Hence, the minor amounts of copper in the alder swamp sedge peat were not extracted from the cupriferous solutions emerging from depth (as in the case of the clearing) but, rather, from the very dilute remnants of those solutions which were filtered through the forest peat of the swampy forest.

The source of the copper must then be sought in either the underlying bedrock or in the ground morainal material. The depth to bedrock is thought to be about 200 feet. This rock consists of the gently dipping gray-green sandstones and conglomerates of the Boss Point formation of Pennsylvanian age. There is reason to believe that the Boss Point was deposited along with slightly cupriferous pyrite (2), with supergene processes yielding local enrichments such as are found at the old Dorchester mine, 7½ miles southwest of the Tantramar swamp. Deeply circulating waters, possibly oxygenated artesian,[5] could remove the copper by dissolution and then percolate up through the ground morainal material and into the copper swamp. Other possible sources are the Dorchester mine itself, and the underlying ground morainal material. The stratigraphy and structure do not contradict the former possibility since artesian waters could have their source in this upland area, and the latter suggestion finds support in the fact that the rock blocks presently lying on the sandy loam of the Tantramar clearing are megascopically similar to the distinctive mineralized grit and conglomerates at Dorchester with the exception that, instead containing small nodules of copper minerals, pits of comparable size are present.

THE TIME FACTOR

In lieu of radio-carbon dating and pollen studies, an attempt to determine the age of the peat can be based on the glaciology of the surrounding region. It is well known that the land was depressed during the Wisconsin glacial maximum as a result of an isostatic response to the weight of the ice. The following climatic rise in temperature with concomitant retreat of the glaciers resulted in a eustatic rise in sea level, which naturally tended to flood the coastal regions, but this effect was partially offset or even overbalanced by the isostatic rise of the land as a consequence of glacial retreat. However, a time lag always exists between the two gradual processes of deglaciation and isostatic recovery.

In the region surrounding the Tantramar area, Flint (5) indicates that strandlines[6] dating from the last deglaciation have risen isostatically 200 feet above present sea level. As the elevation of the copper swamp is now 50 feet, this swamp must therefore have formerly been 150 feet below the present level of the sea, prior to deglaciation. This low ground level oc-

[5] That such waters can occur in nature is exemplified by the Mufulira mine in the Northern Rhodesian Copperbelt. Here, a drill after passing through 300 feet of fresh rock encountered a thoroughly decomposed and oxidized bed at a depth of 2,000 feet (7). At least three artesian wells are known to be present in the Sackville area.

[6] Formed at sea level.

curred during the Wisconsin glacial maximum. Sea level at this time, however, was considerably lower (5) and the Tantramar area could have then been above the sea.

The last glacial advance (Mankato maximum) of the Wisconsin stage occurred around 10,000 years ago in southeastern Canada, and was followed by a general climatic rise in temperature with the cessation of the Ice Age.

With the recession of the glaciers, an eustatic rise in sea level occurred as well as an isostatic rise in the land, but a time lag of as much as 2,000 years existed between the deglaciation and the isostatic recovery (4). This suggests that the Tantramar area was flooded by the sea with the advent of glacial recession, until such a time as the isostatic response compensated for the eustatic rise. Until this occurred, the peat could not form. Flint (4) shows that an acceleration of crustal uplift occurred about 4,000 years ago and the Tantramar area presumably emerged from the sea around this time. If the wood fragments in the peat are autochthonous and the deposit therefore a true forest peat, as Beschel (personal communication) believes, then it could only have formed after the sea receded due to isostatic uplift. The deposit would thus be a maximum of 4,000 years old.

Beschel, while studying the flora of the copper swamp and surrounding area, calculated that a minimum of ½ gallon of water per second flows out of the easterly extension of the clearing via the streamlet; Mackay estimated that 300 tons of copper are present in the swamp. Further, if ½ gallon of solution containing one part per million [7] of copper was introduced per second through the seepages, and arbitrarily assuming that one-twentieth of the introduced copper escaped in the streamlet, then 3950 years would be required to account for Mackay's tonnage estimate. This implies that copper began to be absorbed shortly after the peat began to form and accumulate. It is thus reasonable to assume that waters containing dissolved copper were available since the recession of the Pleistocene glaciers, and that it was these glaciers that exposed copper-mineralized bedrock to the influence of the surficial environment. Likely, therefore, the solutions derived from the weathering of the weakly cupriferous Boss Point formation, not only enriched the Dorchester area,[8] but also supplied the copper which is now present in the Tantramar swamp.

THE ALKALINITY FACTOR

Swamps are noted for their acidity and, in a review of the copper swamps described in the American geological literature (cf. Cornwall, 3), the normal situation appears to be megascopic native copper in peat having a pH of from 4.0 to 6.0. The pH of the peat in other metal-containing swamps, measured by Gleeson,[9] varies from 3.5 to 4.5 at the surface and from 4.8 to 6.0 at the base, the peaty layer most commonly being ten feet thick.

[7] This quantity was implied by Holman's assay of the seepage water in mid-summer.

[8] Brummer (2) relates this type of mineralization to a near surface effect and shows that the enrichment terminates at the present-day water table.

[9] Personal communication; Ph.D. thesis, in preparation, on the "Studies of Metals in bogs" (McGill University).

Conditions in the Tantramar swamp are essentially different. The copper-containing peat is subneutral to slightly alkaline and the metal, being invisible, is thought not to be in a native state. There is the possibility, of course, that this relative alkalinity has its origin in the nature of the cupriferous solutions which have impregnated the organic sediments. The Tantramar peat bank, which has absorbed these cupriferous solutions, is more alkaline than the sandy loam of the clearing, the alder swamp, burnt upland, and normal forest. Thus, the Tantramar peat is more alkaline than both Gleeson's metal bogs and the area surrounding the Tantramar copper swamp.

Since the factors involved in peat formation, such as organic decay and the production of humic acids, result in an increase in acidity, the explanation for the basic nature of the Tantramar peat must lie outside the swamp boundary. The Boss Point formation is of the continental "redbed" type and may locally contain gypsum (8). Further, an extensive salt mass lies about 8,000 feet below the Tantramar swamp, in Mississippian strata, and a fault connects this to the base of the Pennsylvanian. If meteoric waters leached some of the salt mass and moved up the fault, or reacted with the gypsum in the Pennsylvanian redbeds, the resulting alkaline solutions might well enter the copper swamp; perhaps these same solutions were responsible for the breakdown of copper minerals in the bedrock. Many have written on the dissolution powers of the alkaline fluid (10) and geologists are well aware of the arguments supporting this type of solution (albeit generally hot) as chiefly responsible for the transportation of base metals (6). Thus, such a solution may explain both the alkaline and cupriferous nature of the Tantramar peat. This suggestion, however, is offered with some diffidence as it is realized that the present alkaline nature of the Tantramar peat may in actuality bear no relation whatsoever to the composition of the copper-containing solutions.

RECONSTRUCTION

Pre-Carboniferous rocks containing veins of copper and iron sulfides were eroded and slightly cupriferous pyrite was deposited in the lower horizons of the Boss Point formation, either contemporaneously with the sediments or shortly after deposition but before lithification. In a few places, such as at the Dorchester mine, the copper content was increased and concentrated as the result of weathering and subsequent supergene enrichment of the primary, slightly cupriferous, pyrite (2, 9).

During Pleistocene time, about 200 feet of morainal material were deposited in the Tantramar area, containing blocks of Boss Point grit and fine conglomerate. The glacial movement was easterly to northeasterly since the Boss Point is covered by younger Carboniferous sediments in all other directions but south or southwest. Hence, blocks of the well-mineralized lower horizons of the Boss Point formation, originally from the Dorchester area, may well constitute a part of the glacial drift underlying the copper swamp.

With the recession of the glaciers after Wisconsin time, the sea invaded New Brunswick, flooding the Tantramar area until around 4,000 years ago. In the early stages of glacial retreat, melt water deposited a few inches of coarse pink sand. The overlying inch or so of blue clay indicates deposition either by the encroaching sea or by a short-lived shallow post-glacial lake. The removal of ice and water from the Tantramar area, along with a concomitant climatic rise in temperature, resulted in an abundance of vegetation. With the normal death and decay of the plants, a layer of humus formed capable of supporting "forest" growth, typical of many evergreen sections in New Brunswick. Further vegetal decay produced the underlying peat.[10]

Since around 4,000 years are needed to account for the emplacement of the estimated 300 tons of copper, this implies that the metal began to be absorbed shortly after the peat began to accumulate. Thus, it is not unwarranted to assume that waters containing dissolved copper have been available since the recession of the Pleistocene glaciers, and that it was these glaciers that exposed copper-mineralized bedrock to the influence of the surficial environment. Likely, therefore, the solutions derived from the weathering of the weakly cupriferous Boss Point formation not only enriched the Dorchester area but also supplied the copper that is now present in the Tantramar swamp. These solutions may have been further enriched by the solution of copper from the Boss Point blocks in the glacial material beneath the swamp and/or from the weakly cupriferous Boss Point formation immediately underlying the Tantramar area.

The clearing is, of course, a response to copper toxicity. Above the water seepages, the preexisting forest peat absorbed the highest amounts of copper, resulting in the death of the overlying flora. As a gradually widening area developed free from vegetation,[11] rapid evaporation during the summer and the growth of frost crystals in the late fall and winter had the effect of raising the cupriferous solutions to the surface. This modified the dispersion pattern and brought high concentrations of copper into contact with the feeder roots of plants, growing at the southern margin of the clearing and swampy forest, which had hitherto received a degree of protection from the few inches of low-metal humus. This has resulted in the expansion of the clearing southward at the expense of the swampy forest. This progressive poisoning is still active (1) as new trees die every year in this marginal area.

Rain, along with the water from the seepages, has eroded the peat in the clearing, thereby exposing the underlying clay and glacial material. The outflowing streamlet is at present steadily eating away at the bare peat bank and this effect, along with solifluction phenomena, has tended to move the dislodged peat muck eastward towards lower ground. This process has resulted in the introduction of excessive copper concentrations to the feeder roots of plants at the eastern margin of the clearing, and is thus responsible

[10] The alder swamp appears to be an exception, as there is no evidence that forest growth occurred in this sector (1).

[11] Beschel (1) believes that around the year 1900 a bush fire aided in the establishment of the clearing.

for the extension of the bare area in this direction. The end result is clearly the destruction of the swamp forest along with a concomitant development of a low-copper dispersion train in the sediments of the easterly flowing streamlet.

SUMMARY

1. The area studied can be conveniently divided into a number of sectors, having the following maximum copper content:

Sector	Soil	Maximum copper
Copper Swamp		
(a) clearing	sandy loam	1 percent
	forest peat	10 percent
(b) swampy forest	humus	1 percent
	forest peat	5 percent
Alder Swamp	sedge peat	0.1 percent
Burnt Upland	loam	less than 0.01 percent
Normal Forest	loam	less than 0.01 percent

2. The Tantramar copper swamp seems unique in that up to ten percent copper is contained invisibly in subneutral to slightly alkaline peat. This contrasts sharply with what appears to be the normal situation of lumps and aggregates of native copper in a swamp of acidic pH.

3. The cupriferous solutions enter the Tantramar swamp from below, emerging as seepages in the clearing. The copper is definitely not transported to the swamp by surface streams.

4. The rate of soil irradiation (evaporation) has an important affect on the dispersion pattern of the copper in the swamp sediments. In bare areas, the greatest copper quantities occur at the surface whereas, in forested areas, the higher copper zones are found at a depth of two or three feet.

5. The source of the copper must be sought in the weakly cupriferous Boss Point formation, either (a) in local supergene enrichments such as the old Dorchester mine, (b) in the unenriched horizons directly beneath the swamp, and/or (c) in the morainal Boss Point blocks underlying the swamp.

6. The age of the peat is estimated at 4,000 years, and the tonnage of copper contained in this peat implies that the metal began to be absorbed shortly after the formation of the organic sediment. It is believed that cupriferous solutions were available since the Pleistocene Ice Age, when copper-mineralized bedrock was exposed to the influence of the surficial environment by erosive glacial action.

7. The clearing is the result of copper toxicity, and it is presently expanding at the expense of the swampy forest. If this trend continues, the swampy forest will be ultimately destroyed.

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STUDIES ON THE OXIDATION OF MAGNETITE

K. V. G. K. GOKHALE

ABSTRACT

This paper summarizes the investigation carried out to elucidate the processes and products of magnetite on oxidation during dry heating. Magnetite, on dry heating undergoes oxidation with no concomitant change in structure except for cell contraction; the X-ray powder patterns of such oxidized magnetites are similar to that of maghemite. By further oxidation, hematite exsolves as a separate phase and after prolonged heating at 800° C, magnetite is completely oxidized to hematite. The petrogenetic significance of these studies is also discussed.

INTRODUCTION

THE equilibrium relations between Fe_2O_3-Fe_3O_4-O system determined by Posnjak and others, relate to the oxidation states of iron in igneous rocks that are known to have been formed at very high temperatures. Existence of hematite within magnetite is also known in metamorphic environments. It is thought quite possible, that a part of the hematite is the oxidized product of magnetite formed during metamorphism. In order to elucidate the exact process of oxidation, the author carried on a series of experiments on the oxidation of iron oxides in air at temperatures between 400°–800° C, commonly prevalent under various metamorphic conditions. Studies on heat treatment of magnetite have been reported from time to time, by workers like Gruner (1926), Posnjak (1925) Welo & Baudisch (1925), Twenhofel (1927), Grieg et al. (1935), and others. Most of their materials, in some cases, have been heated in vacuo and in others the materials studied were either powdered or synthetic magnetite. The results of their investigation depart from the results one would obtain from such heat treatment of natural polished specimens and hence their experimental conditions do not duplicate the conditions found in nature. In the following pages the experimental procedures are described, the methods of investigation are detailed, and a critical discussion of the nature of oxidation of magnetite is presented.

STATUS OF PRESENT KNOWLEDGE

The problem of oxidation of magnetite has received considerable attention for over a century. The existence of an oxidized magnetite was discovered by Robbins (8). Sosman and Posnjak (9) oxidized synthetic magnetite (prepared by chemical precipitation by a solution of NH_4SO_4 and by air at 105° C). The resulting oxidized material was reported to be highly magnetic and to have an X-ray pattern similar to natural pure magnetite.

Welo and Baudisch (1) oxidized magnetite to hematite in a stream of oxygen at about 220° C and conceived the change from magnetite to hematite to be a "two-stage" one, the magnetite first changing to oxidized magnetite at 220° C, at which time the oxidation process was complete and no further iron was present, and then inverting to hematite at about 550° C. They regard both of these changes as being sudden and occurring at fixed temperatures.

Gruner (5) reported the formation of hematite along octohedral planes of magnetite with differences in depth of penetration of the oxidation and its rate of occurrence; these differences were attributed to variations in the grain size on the principle that small grains, having greater surface energy than the larger ones, permit greater diffusion of oxygen atoms in the magnetite space lattice.

Twenhofel (11), while verifying and supplementing the conclusions of Welo and Baudisch (1) and of Sosman et al. (9), concludes that the intermediate oxidized product from magnetite to hematite is identical to magnetite in its structure and states that the oxygen atoms, which are added when oxidized magnetite is formed, are irregularly spaced within the magnetite crystal structure. Their exact position was not reported.

Hugget and Chaudron (5a) studying the temperature of the magnetic transformation in the system Fe-Fe_2O_3 made a number of mixtures ranging in composition between Fe_2O_3 and Fe_3O_4 by reducing Fe_2O_3 with H_2 and heating the product at 650° C to homogenize the oxide or oxides. They report two reversible transformation, one at 570° corresponding to that of magnetite, and the other at 650° which they attributed to a saturated solution of Fe_3O_4 in Fe_2O_3.

Grieg et al. (4) studied the equilibrium relationship of Fe_3O_4, Fe_2O_3 and O_2 over a limited range of high temperatures. According to them, magnetite (solid solution) at 1,075° C containing $92 \pm 1\%$ of Fe_3O_4 and $8 \pm 1\%$ Fe_2O_3 can co-exist in equilibrium with hematite containing less than 0.5% of Fe_2O_3 and oxygen under a low pressure. Their studies comprised the oxidation, dissociation, sintering, recrystallization and unmixing, and on structures developed by these processes as seen under the microscope. But all those conclusions, mostly are based on experimental work done at higher temperature levels of 1,000° C and more.

Gheith (3) experimenting on synthetic and natural magnetite obtained in thermal analysis two exothermic peaks caused by initial oxidation to ν-Fe_2O_3 and subsequently to hematite.

Schmidt and Vermaas (10) made a study of the behavior of magnetite on heating, and concluded that magnetite goes through two stages of oxidation on being heated in air, the first stage being a surface oxidation to hematite followed by a second stage when complete oxidation of hematite takes place. No formation of ν-Fe_2O_3 was detected at any stage.

More recent studies by Lepp (6) suggest a three stage oxidation of magnetite first to ν-Fe_2O_3 at 375°–400° C and then to α-Fe_2O_3 at 525–550° C, which finally transforms to hematite at 575° C.

EXPERIMENTAL PROCEDURE

For the present investigation, several magnetites from the author's own collection and also from Kranz's (W. Germany) collection have been used. These specimens were well polished and were heated at 400, 600 and 800° C respectively for 2 to 6 hours in a thermostatically controlled furnace. After heat treatment, these samples were quenched and subjected to different tests to study the changes in different properties at each temperature level.

Vicker microhardness determinations were made at various stages of transformation of magnetite through heating in air. The indentation diagonals were studied under the microscope.

Several X-ray powder patterns were taken with a 57 mm camera using cobalt K_α radiations. The d values for magnetite and the oxidized products at each subsequent level were measured. After applying proper shrinkage correction, values for the lattice parameter (a_0), calculated from the high angle lines, were obtained by the graphical extrapolation method. In this method the different values of cell edge (a) are plotted against $\text{Cos}^2\theta$ and the value for a_0 recorded where the $\text{Cos}^2\theta$ is equal to 0. The results of lattice parameters at various temperatures are listed in Table 2. Since oxidation appears to be a surface phenomenon, a few of the samples were powdered and analyzed for X-ray powder patterns at all the temperature levels, as was done with the polished specimens.

The samples used in the present study were thermally analyzed. The specimens were ground to pass through a 250 mesh screen and correspondingly fine grained Al_2O_3 powder was used as the inert material. The rate of heating was kept constant at 10° C per minute up to 1,000° C.

METHODS OF INVESTIGATION AND RESULTS

It is the purpose of this study to

(a) describe the microscopic features of magnetites and the oxidized products;

(b) to determine the variation of hardness on thermal treatment;

(c) to correlate the curves determined by D.T.A. methods with the oxidation stages of magnetite; and

(d) to study the different iron-oxide patterns of oxidizing magnetite, both before and after heat treatment.

As is stated below, this study has helped in the understanding of "maghemite" and its relation to magnetite and hematite.

Ore Microscopic and Microhardness Studies.—Polished specimens of magnetite show under the microscope the effects of oxidation at 400° C. The Vicker's hardness (H_v) values are plotted against the test load (t) in grams (Fig. 1). It is seen that the natural magnetite samples taken for the present study have a peak value of H_v at 50 grams load and the value gradually falls with subsequent high loads. Nakhla (7) has shown that the curve for magnetite falls off gradually at higher loads and no peak is noticed. It is seen that on

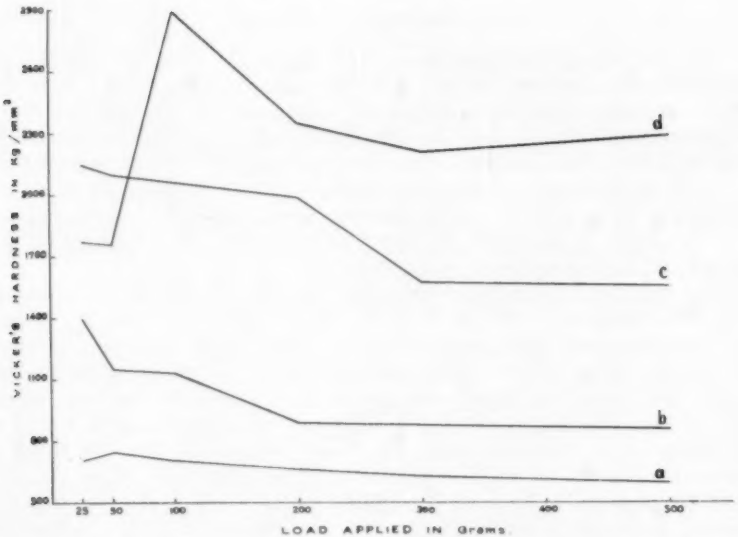

FIG. 1. Vicker's hardness curves for magnetite (a) natural, (b) at 400° C, (c) at 600° C; and for (d) exsolved hematite at 600° C.

heating during the process of oxidation, the original indentations at higher temperatures disfigure, and though the average value of the indentation diagonals remain constant, one of the diagonals increases with a decrease of the other. Hardness values at 400° C and 600° C are also determined and the variation is shown in Table 1 and indicated in Figure 1.

At 400° C the hardness increases and the values for the samples lie between 850 and 1,400. There is a gradual decrease of hardness at higher loads. At 600° C, hematite exsolves from magnetite along the cleavage directions in magnetite and also along grain boundaries. Ore microscopic examination revealed Widmanstetten type of texture for the heat treated specimens at 600° C. The hardness values of both exsolved product (hematite) and the

TABLE 1

MICROHARDNESS (H_v) VALUES IN KG/MM

Test load	Natural magnetite	Oxidized magnetite (400° C)	Oxidized magnetite (600° C)	Exsolved hematite (600° C)
25	702	1,402	2,145	1,768
50	750	1,145	2,100	1,764
100	700	1,140	2,056	2,892
200	657	882	1,997	2,353
300	623	865	1,569	2,212
500	607	858	1,563	2,283

oxidized magnetite are indicated in Table 1 and Figure 1. It is seen from the table, that for the oxidized magnetite, the values vary from 1,563 to 2,145 and the curve has a drooping nature with the test load. This is almost sympathetic with the previous curve at 400° C but the values are comparatively higher. For the exsolved hematite portion, the hardness was much higher, varying from 1,264 to 2,892. It has a peak value at 100 grams load ($H_v = 2{,}892$) and again the value of H_v is found to be 2,283.

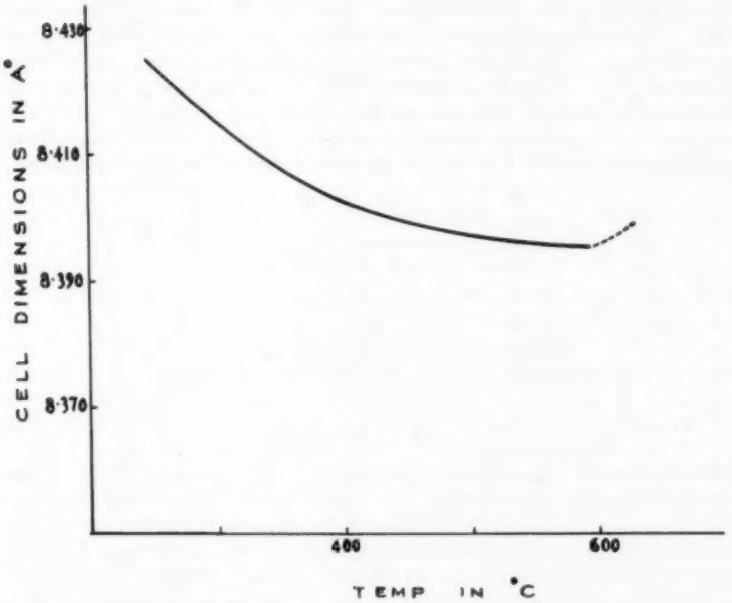

FIG. 2. Variation of the cell edge (a_0) with temperature.

With still higher temperature at 800° C, microscopic observations of the heat-treated samples indicate that the exsolved hematite concentrates more and more in patches, and finally with prolonged heating for 10 to 12 hours, they are almost completely converted to hematite. On polished sections, the complete conversion is not noticed by x-rays since the oxidation is a superficial phenomenon, but with prolonged heating at 800° C of powdered magnetite, the x-ray powder patterns indicate complete and thorough conversion to hematite.

Thermal Analysis.—The D.T.A. for magnetites revealed a shallow exothermic peak at 100° C, and a very sharp exothermic peak at 600° C. Similar peaks at such temperature ranges have been reported earlier by Gheith (3), Schmidt and Vermaas (10). The shallow endothermic peak at 100° C is due to dehydration. As regards the sharp exothermic peak at 310° C the

author does not quite agree with the views expressed by Gheith that this peak is due to recrystallization of the magnetite grains present. Probably this is due to the oxidation of magnetite itself, and the changes noticed in the X-ray studies at this temperature, and discussed later in the text, support this conclusion. At 600° C the flat exothermic peak is quite characteristic and is due to exsolution that is evidenced in X-ray and microscopic (textural) study.

X-ray Study.—The X-ray study indicated a distinct shift of the lattice reflections towards higher values for heat treated specimens at various temperatures. As a consequence the cell constant (a_0) decreases with temperature up to 600° C (Fig. 2), and is due to shrinkage of the cell (detailed in subsequent pages). The cell value after 600° C rises and no extra lines for hematite, even at 800° C, are noticed due to surface oxidation. But with heat treatment of powdered magnetite, conversion to hematite as an end product is noticed at 800° C when the powder is heated for 8 to 10 hours.

TABLE 2

CELL DIMENSIONS OF MAGNETITE AT VARIOUS STAGES OF OXIDATION

a_0	Temp.
8.425	Magnetite
8.402	Magnetite at 400° C
8.395	Magnetite at 600° C
8.457	Magnetite at 800° C

DISCUSSION

The oxidation of magnetite to hematite does not appear to be a simple direct step. Schmidt and Vermaas (10) believe that the oxidation takes place in two distinct stages. As has been mentioned earlier according to them the early stage consists of superficial oxidation to hematite followed by complete conversion with no formation of any intermediate product. Henry Lepp (6) who worked on the stages of oxidation of magnetite suggests three stages. The author's conclusions cannot support either of these views.

With heat treatment of the magnetites, there is a distinct decrease in cell volume as shown in Table 2. A contracting cell appears to be a characteristic of heat-treated magnetite. This contraction can be explained only as an indication of phase change within magnetite structure. Generally on heat treatment, one observes cell expansion due to thermal effects. But a distinct contraction is a definite indication that in spite of such thermal effects, there is observable lattice modification. However, after reaching a minimum cell dimension at about 600° C, there is again a notable cell expansion. This indicates that after 600° C, there is an arrest of such lattice contraction. No further causes can be adduced at this stage for the cell expansion after 650° C, except probably that it is due to thermal expansion.

The entry of oxygen atoms into the magnetite not only increases the stoichometric ratio of oxygen to iron, but also probably converts the valency

state of iron as follows

$$\underset{(Fe'')}{Fe_3O_4} + \tfrac{1}{2}O \rightarrow 1\tfrac{1}{2}\underset{(Fe''')}{(Fe_2O_3)}.$$

Thus in one way the oxidation may be looked upon as a conversion of magnetite to hematite on an atomic scale. Many have expressed doubts on the possibility of magnetite-hematite solid solutions. For instance Gruner (5) had no reason to believe that a solid solution exists between magnetite and hematite. Based on the analogy that if the magnetite-ilmenite system can have a fairly large field of solid solution at high temperatures, then why cannot magnetite-hematite systems also mix together at high temperatures since hematite and ilmenite have a similar structure.

Thus, the oxidation of magnetite can be looked as a gradual solid solution of magnetite with hematite, the latter increasing with the consequent decrease of the former. The X-ray and ore-microscopic evidence suggests a single phase until about 600° C, after which there is the formation of a "free" hematite phase. Until the temperature reaches 600° C, however, there is an indication of increased oxidation of magnetite. Since no "free" hematite phase could be detected, it can be concluded that whatever "hematite" is formed, it is held in solid solution by magnetite, which may be looked upon as a "hematitic magnetite," an intermediate structural phase between the magnetite and hematite stages. The cell dimensions of the intermediate phase, are in close agreement with data given for maghemite. However, it can be stated clearly here, that the author does not clearly visualize maghemite as a distinct intermediate phase, but as a continuous transition between magnetite and the oxidized magnetite prior to the formation of "free hematite." Some authors termed the intermediate phase due to oxidation of magnetite as ν-Fe_2O_3. Since the structure of this intermediate phase is more closely related to magnetite structure, it is more precise to define it as a ν-Fe_3O_4. The author is of the opinion that this ν-Fe_3O_4 has no definite cell constants but a varying dimensions (a_0) between 8.398–8.425, changing with the state of oxidation.

The oxidation appears to start even at very low temperatures, such as less than 400° C where even evidences of oxidation are noticed. If the magnetite powder were to be heated for a long time (8–10 hrs) the oxidation may be as perceptible, even at still lower temperatures. However when the heating is at about 600° C, there appears to be another distinct phase separation. This can be correlated with the D.T.A. peak that is observable in this region. Microscopic evidence also suggests of the formation of Widmanstetten intergrowths at this temperature range. The X-ray study of cell edges at this temperature suggests of a phase change. This suggests the manner of oxidation is as follows: Magnetite, taking up excess oxygen atoms, becomes converted to hematitic magnetite (maghemite?). There appears to be a partial solid solution between Fe_3O_4 and Fe_2O_3 with the result, that after magnetite is saturated with a quantitative phase of hematite within solid solution, any further oxidation could result in the formation of hematite as a free-phase. Further heating at a temperature above 600° C

aids in the formation of hematite from maghemite (?) type of material. Evidences of exsolution textures support these conclusions. Prolonged heating at about 800° C convert completely the entire maghemite into hematite as seen in X-ray pattern.

The position of martite in the above sequence is dubious. Since no X-ray data are available it is not possible to compare these lattice spacings and look for the identification of martite in the oxidation states of magnetite. Probably it is hematite replacing magnetite, a process that is quite distinct.

Thus the author pictures the oxidation of magnetite as follows:

Magnetite $\xrightarrow[\text{(continuous change)}]{}$ maghemite (?) of variable comp.

maghemite (?) $\xrightarrow[\text{(discontinuous change)}]{}$ hematite.

The "free" hematite phase is formed after complete oxidation of magnetite to oxidized magnetite (maghemite?), which will be complete by about 600° C.

PETROGRAPHIC SIGNIFICANCE

The studies on oxidation of magnetite cannot possibly be directly applied to the correlation of oxidation states of iron oxide minerals in nature. Although magnetite is a minor accessory found in all rock types, these studies will probably help to a great extent in the studies on metamorphic rocks. In igneous rocks, the changes of oxidation of iron oxides take place in a system of cooling thermal environment with simultaneous crystallization; whereas in metamorphic rocks, oxidation of magnetite takes place during the increase of temperature from lower to higher levels. The latter conditions are more analogous to the experimental study presented here; barring of course the effects of pressure, if any, which has not been studied in the present set of experiments.

There is another complicating factor in the presence of TiO_2 in the system. Not only is Fe_3O_4 oxidized, but also it may convert into ilmenomagnetite. It is not rare to see in certain rocks, the formation of ilmenite-magnetite and ilmenite-hematite-magnetite intergrowths. Another major difficulty is the assumption that in metamorphic rocks, the hematite observed, is secondary after magnetite, formed during the stages of oxidation concomitant with increasing grades of metamorphism. In many of the metamorphic rocks, hematite also forms as an independent primary mineral. But it can be assumed that independent grains of hematite cannot preferentially go into solid solution with the magnetite, during the oxidation of magnetite. Any hematite (other than primary) found as a part of a magnetite grain is a certain indication of the oxidation of magnetite to at least temperatures around 600° C. It is also found that dependent on the state of oxidation, the magnetite cell shows variable dimensions. The variable cell constants is

possibly an indication of the changing state of oxidation of magnetite, which can be used indirectly as a geologic thermometer.

Buddington et al. (2) suggested that the variable amount of TiO_2 in Fe_3O_4 can possibly be used as a geologic thermometer. At higher temperatures, the magnetite not only shows a greater solubility for TiO_2 but itself undergoes oxidation. Since these processes are concomitant, it is reasonable to assume, that these processes are interdependent. So the states of oxidation of magnetite may be useful as geological thermometer in case of rocks that have small amounts of TiO_2. Also magnetite cell dimensions with temperature may have thermometric significance. Further work on the cell dimensions of maghemite in relation to the grade of metamorphism of rock types, is now under investigation.

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BAUXITE IN SARAWAK[1]

E. B. WOLFENDEN

ABSTRACT

Sarawak bauxite deposits are briefly described and are shown to have formed on a large scale only from intermediate and basic igneous rocks. The bauxite was formed under humid tropical conditions, and its formation was controlled to a large degree by the hydrogen ion concentration of the groundwater.

INTRODUCTION

BAUXITE was located in west Sarawak by the Geological Survey Department in 1949, and the British Aluminium Company Limited prospected the area from 1950 to 1952. Several bauxite deposits were found, and three appeared to be of economic value, containing about 5½ million tons of washed bauxite and being easily accessible. In 1957 a local company, Sematan Bauxite Limited, started mining bauxite at Munggu Belian, Sematan, and has since exported about 550,000 tons of ore. In 1961 the same company plans to start mining a second deposit, at Bukit Gebong, about 5 miles southeast of Sematan. Bauxite has been Sarawak's most valuable mineral product since 1959.

Sarawak bauxite is described in memoirs of the Geological Survey Department, British Territories in Borneo, by Haile (4, 5) and Wilford (16), and additional features are recorded in departmental annual reports by Roe and Haile (14), Haile (6, 7), and Wolfenden (17, 18). The detailed survey of the Sematan and Lundu areas by Haile and the writer, started in 1960, has added greatly to knowledge of the bauxite. The correct identification of the source rocks from which the bauxite has been formed has discredited many earlier ideas on its origin. Even so, this account is only provisional, as the results of tests on many samples from bauxite deposits are not yet known. These results will probably not affect the broad conclusions of this paper, but will add greatly to an understanding of the details of the processes by which bauxite is formed. In the future, a detailed account will be prepared incorporating these results.

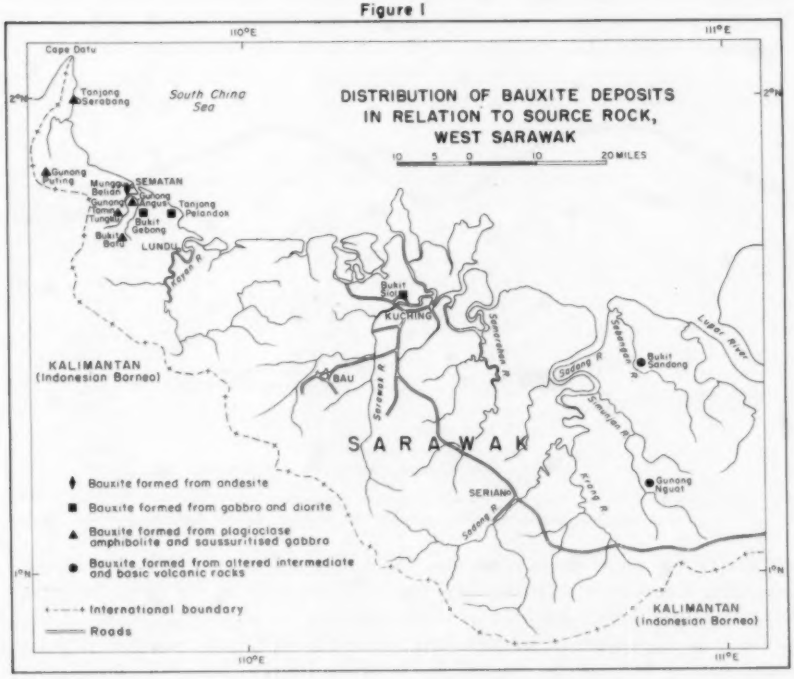
DEFINITION OF BAUXITE

Bauxite has been variously defined by different authorities. Harder (8) defined it as "an aluminium ore, more or less impure, in which the aluminium is largely present as hydrated oxides." This definition is rather unsatisfactory as specifications for aluminium ore vary considerably because of changing

[1] Publication authorized by the Director, Geological Survey Department, British Territories in Borneo.

economic conditions. Other definitions have been proposed, including one based on mineralogical and chemical criteria by Gordon et al. (3); this, however, cannot be used here as it requires detailed information not yet available for most of the Sarawak bauxite. The term bauxite is here restricted to rocks containing more than 40 percent alumina; bauxite is termed low-alumina bauxite if the alumina content is less than 50 percent and high-alumina bauxite if the alumina content is greater than 50 percent. The

Figure 1



main impurities in bauxite are silica and iron; bauxite is termed siliceous bauxite if silica is greater than 5 percent, and ferruginous bauxite if ferric oxide is greater than 10 percent.

Mineralogically, Sarawak bauxite consists principally of gibbsite, the trihydrate of alumina ($Al_2O_3 \cdot 3H_2O$), with various impurities, including quartz and possibly kaolinite-type clay minerals, the oxides and possibly hydroxides of iron, and the oxides of titanium.

DISTRIBUTION OF BAUXITE AND RELATION TO BEDROCK

Bauxite has been found in Sarawak only in the area west of the Lupar River (Fig. 1). It shows a definite relationship to the nature of the bedrock, and has formed on a large scale only from intermediate and basic

igneous rocks. The bauxite is described in relation to the rock from which it has formed, and four types of source rock are recognized: (1) andesite, (2) gabbro and diorite, (3) plagioclase amphibolite and saussuritized gabbro, and (4) altered intermediate and basic volcanic rocks.

In addition, small amounts of bauxite occur at several localities in soil overlying rocks of such varied composition as shale and basalt. The bauxite at the different localities is similar in macroscopic and microscopic appearance and chemical composition. Little is known about the origin of this bauxite, but it is suggested that the nodules formed by the migration and segregation of alumina within the soil, and not directly from the underlying rocks.

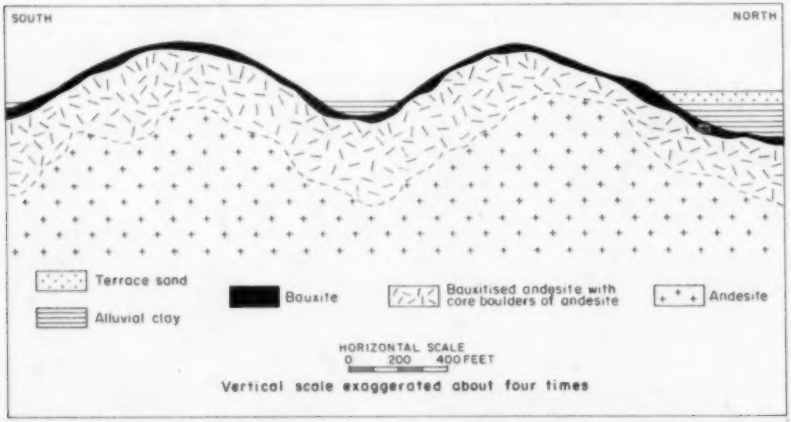


Figure 2 Diagrammatic section across the Munggu Belian bauxite deposit

Bauxite Formed from Andesite.—Pyroxene andesite at Munggu Belian, Sematan, forms hills less than 100 feet high, flanked on the north and west by terrace alluvium, and on the south and east by alluvial swamps. Large amounts of high-alumina bauxite have formed from this andesite; a diagrammatic section through the deposit is shown in Figure 2.

Unaltered andesite has been found only as core boulders in bauxite and underlying bauxitized andesite. The andesite is a fine-grained, porphyritic, greenish-gray rock, with sub-parallel vesicles. It contains phenocrysts of orthopyroxene, clinopyroxene, and pseudomorphs possibly after olivine, in a fine-grained groundmass of sodic andesine and pyroxene with accessory magnetite and rutile; the plagioclase laths show a parallel orientation; some vesicles contain fine-grained zeolites. The composition of the andesite is given in Table 1. The andesite core boulders have a skin of buff bauxitized andesite composed of pseudomorphs of microcrystalline gibbsite after plagioclase, iron-stained pseudomorphs after pyroxene, and magnetite and rutile. The analysis (Table 1) shows significant alumina enrichment compared with the unaltered andesite; the high silica content may indicate the presence of kaolinite-type clay minerals.

Slightly more than 2½ million tons of high-alumina bauxite (Table 1) have been proved at Munggu Belian; recent prospecting has shown that bauxite extends below the alluvium, but its full extent is unknown. The thickness of bauxite ranges from 1 to 18 feet, averaging about 10 feet; clay overburden is as much as 4 feet thick on the hills. Where the bauxite passes below alluvium the thickness of overburden increases markedly, and in places is as much as 50 feet.

The bauxite occurs as hard, pink-brown and gray nodules from about a quarter of an inch to a foot across, averaging about 1½ inches. The nodules are scattered in a buff or brownish-red clay; usually the buff clay overlies the brownish-red clay. Near the base of the bauxite the proportion of clay increases, and the bauxite nodules are softer and occur as irregular more or

TABLE 1

ANALYSES OF ROCKS FROM MUNGGU BELIAN, SEMATAN

Rock type and sample number	Pyroxene andesite S5787	Bauxitized andesite S6108	Bauxite S4698
SiO_2	52.49	34.72	1.98
Al_2O_3	17.70	29.51	56.08
FeO	5.84	15.60[a]	9.04[a]
Fe_2O_3	2.16		
MgO	4.16	0.58	nil
CaO	7.39	0.06	nil
Na_2O	3.98	n.d.	n.d.
K_2O	1.00	n.d.	n.d.
H_2O+	1.83	17.28[b]	31.37[b]
H_2O-	1.40	2.90	1.70
TiO_2	1.82	0.23	0.30
P_2O_5	0.83	n.d.	n.d.
MnO	0.10		
Total	100.70	98.88	100.17

Analyses by Mineral Resources Division, Overseas Geological Surveys, London.
[a] Total iron calculated as Fe_2O_3.
[b] Loss on ignition.
n.d. = not determined.

less horizontal sheets. The bauxite shows the sub-parallel vesicles of the source rock, the vesicles commonly being filled with gibbsite. Thin sections clearly show the trachytic texture of the parent andesite. Plagioclase laths have been pseudomorphed by microcrystalline gibbsite, pyroxene crystals have been pseudomorphed by iron minerals with some gibbsite, and the magnetite and rutile of the andesite are unaltered.

Underlying the bauxite is massive, soft, buff bauxitized andesite, which in places is more than 60 feet thick. The transition from bauxite to bauxitized andesite is generally quite marked, taking place within a few inches. The bauxitized andesite is closely similar in chemical composition to the bauxitized skin of the core boulder (Table 1). Thin sections of the bauxitized andesite show the trachytic texture of the parent andesite, and consist of pseudomorphs of microcrystalline gibbsite after plagioclase, iron-stained pseudomorphs after

pyroxene, and magnetite and rutile; plagioclase altered before pyroxene. The high silica content of the rock suggests that kaolinite-type clay minerals are probably present.

Bauxite Formed from Gabbro and Diorite.—Gabbro and diorite have been altered to bauxite at several places in west Sarawak, but only one deposit, at Bukit Gebong, 5 miles southeast of Sematan, has been thoroughly examined.

Bukit Gebong is a steep-sided hill 1,097 feet high, formed of medium- to coarse-grained gabbro, ranging from olivine gabbro to quartz gabbro. The gabbro is deeply weathered, in places to more than 90 feet, and large amounts of bauxite have been formed. The thickness of bauxite ranges from 1 to 23 feet, averaging 7 feet; clay overburden is as much as 6 feet thick. Gabbro boulders of all sizes up to 40 feet across are mixed with the bauxite. Other boulders from about 6 inches to 3 feet across, which appear outwardly to be solid bauxite, actually consist of a skin of bauxite surrounding a core of unaltered gabbro, the transition taking place within 1 to 2 mm.

Prospecting by Sematan Bauxite Limited indicates that about 1½ million tons of washed bauxite occurs at Bukit Gebong, comprising two grades as follows:

Al_2O_3	Total SiO_2	Fe_2O_3	TiO_2	Loss on ignition	Tonnage
52.10	4.66	13.14	0.49	29.61	760,477
46.97	7.27	18.02	0.57	27.17	828,904

The composition of the bauxite appears to vary rather capriciously, with areas of high-alumina bauxite surrounded by areas of siliceous, ferruginous, low-alumina bauxite. A. W. Allen (1) states that the composition of the bauxite can be related to altitude, the alumina content increasing and the silica content decreasing at higher levels on the hillside; a plot of these two oxides in relation to altitude shows, however, that there is no correlation.

The bauxite from Bukit Gebong is commonly rather friable, porous, and reddish-brown or yellowish-gray with white specks. Much of it is massive, pieces about 8 inches across being common, but smaller nodules also occur, and a variable amount of clay is present. The texture of the parent gabbro can be recognized in thin sections. Mosaics of microcrystalline gibbsite form pseudomorphs after plagioclase, and iron oxide (limonite?) occurs along cracks and cleavages and forms hollow pseudomorphs after olivine and pyroxene. Bauxite formed from quartz gabbro contains quartz crystals derived from the gabbro, and much of the silica in siliceous bauxite is present as free quartz, not as clay minerals.

Underlying the bauxite is clay, and a pit 90 feet deep at the eastern end of the deposit failed to reach gabbro. The variation with depth in chemical composition of the bauxite and clay is shown in Figure 3. The chemical change from bauxite to clay is quite marked, taking place between 15 and 17 feet in the pit. The mineralogy of the clay is difficult to determine microscopically, but it commonly contains a few quartz crystals in a fine matrix

of gibbsite or clay minerals, heavily stained with iron oxide. A significant feature of the clay is that no relic igneous texture can be discerned, but it has so far only been possible to examine samples from directly below the bauxite. Gordon et al. (3, p. 102) described clay, occurring between bauxite and nepheline syenite in Arkansas, U. S. A., which was textureless adjacent to the bauxite, but showed an igneous texture at depth.

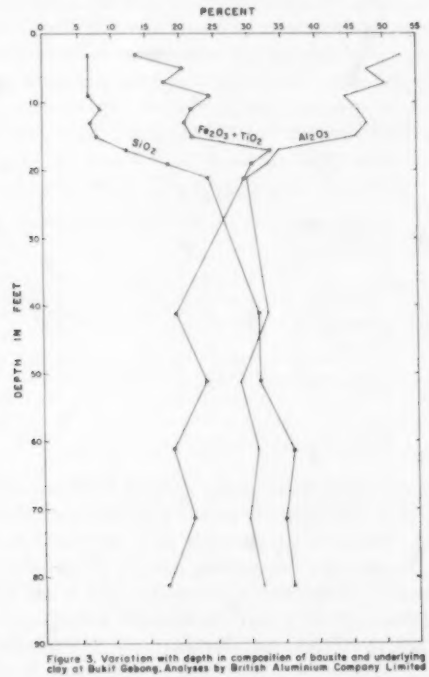


Figure 3. Variation with depth in composition of bauxite and underlying clay at Bukit Gebong. Analyses by British Aluminium Company Limited

Elsewhere in the Sematan and Lundu areas, bauxite has formed from gabbro and hybrid rocks of dioritic composition. The type of bauxite formed is governed by the nature and composition of the source rock. East and south of Tanjong Pelandok, two gabbro intrusions have been extensively hybridized by a granite intrusion, and rocks of dioritic and tonalitic composition containing large poikilitic quartz crystals have formed. Bauxite formed from gabbro is similar in composition and mineralogy to that at Bukit Gebong, but that formed from hybrid rocks is high in silica (Table 2), as the quartz crystals in the parent rocks are unaffected by the bauxitization.

Evidence from bauxite at Bukit Siol, near Kuching, supports this conclusion. This bauxite formed from quartz diorite and is high in silica, as free quartz in the diorite was not removed during bauxitization.

Bauxite Formed from Plagioclase Amphibolite and Saussuritized Gabbro.—Altered basic igneous rocks are common in the Sematan area. The degree of alteration varies considerably, and the rocks range from slightly altered, uralitized and saussuritized gabbro, as at Gunong Angus, to plagioclase amphibolite, as at Tanjong Serabang, which is so intensely altered that its original nature is difficult to determine. Rocks from the Serayan Valley, south of Sematan, illustrate the progressive change from ophitic gabbro to plagioclase amphibolite, apparently identical with that at Tanjong Serabang. The gabbro consists of laths of labradorite, crystals of diallage, and accessory iron ore. Dynamic metamorphism and saussuritization have altered this rock to give plagioclase amphibolite composed of albite and actinolite, with various amounts of hornblende, and accessory iron ore, clinozoisite, calcite, and some quartz; the amphibolite shows a typical cataclastic texture, closely similar to that described by Harker (9)

TABLE 2

ANALYSES OF SILICEOUS BAUXITE FORMED FROM HYBRID ROCKS

Sample number	Locality	Al_2O_3	Total SiO_2	Fe_2O_3	TiO_2	Loss on ignition
S7374	Munggu Makissam, east of Gunong	51.20	15.80	3.35	2.25	26.40
S7375	Pandan	43.35	27.85	4.75	1.05	23.00
S7400	Sungai Nangkut, tributary of Sungai Bajo	44.40	26.90	3.70	1.55	23.45

Analyses by Sematan Bauxite Limited.

Bauxite has been formed from such rocks at Tanjong Serabang, Gunong Angus, Gunong Tamin Tungku, Gunong Puting, and Bukit Batu. Many pits were dug during previous prospecting at these localities, but the location of most of them and their relation to the geology is uncertain.

The most thoroughly examined of these deposits is at Tanjong Serabang, where it is belived that about 1 million tons of ferruginous bauxite occurs, containing an average of 47 percent alumina and 6 percent total silica. The average thickness of bauxite is 5 feet, and it occurs as hard, reddish-brown pebbles and nodules in a reddish-brown clay. The bauxite is overlain by as much as 4 feet of clay, and is underlain by variegated clay.

The other deposits have not been examined in detail. Two pits at Bukit Batu penetrated 32½ and 8 feet of ferruginous, low-alumina bauxite, composed of microcrystalline gibbsite and an iron mineral, probably limonite, and showing the cataclastic texture of the amphibolite from which it formed. At Gunong Angus, five pits were dug in bauxite; the average thickness of ore was 7 feet, and the quality varied from bauxite with 59.85% Al_2O_3 and 3.06% total SiO_2, to 49.12% Al_2O_3 and 10.48% total SiO_2. Ferruginous, siliceous, low-alumina bauxite was found at most of the other localities.

Bauxite Formed from Altered Intermediate and Basic Volcanic Rocks.—Altered intermediate and basic volcanic rocks, lavas, tuffs, agglomerates, and breccias, are widespread in west Sarawak, and have been described by Haile

(4) and Wilford (16). Most of the lavas are andesite or basalt, with phenocrysts of augite, rare olivine, and plagioclase, in a groundmass of plagioclase and pyroxene. The rocks are intensely altered, being chloritized, prehnitized, silicified, serpentinized, and calcitized.

Bauxite, apparently in small amounts, has been formed from such rocks at Bukit Sandong in the Sebangan Valley, and in the Bukit Punda and Gunong Nguat areas in the Simunjan Kanan Valley. The bauxite is of varied grade but is commonly low in alumina, high in silica, and invariably high in iron and titanium oxides (Table 3). A pit in the Bukit Punda and Gunong Nguat area penetrated 12 feet of low-alumina bauxite below 7 feet of clay overburden; the bauxite was underlain by clay.

TABLE 3

ANALYSES OF BAUXITE FORMED FROM ALTERED VOLCANIC ROCKS

Sample number	Locality	Al_2O_3	Total SiO_2	$Fe_2O_3+TiO_2$	Loss on ignition
—	Bukit Sandong	44.09	2.77	28.80	28.34
4582		57.34	3.54	10.96	28.16
4583	Bukit Punda and	53.14	3.82	15.20	27.84
4584	Gunong Nguat area,	45.39	16.09	15.44	23.08
4585	Simunjan Kanan	44.71	7.85	23.76	23.68
4741	Valley	49.28	14.26	11.36	25.10

Analyses by British Aluminium Company Limited.

ORIGIN OF THE BAUXITE

Although bauxite has been formed from a wide variety of rocks in different parts of the world, in Sarawak it has been formed only from intermediate and basic igneous rocks. Harrison (10) showed that under tropical conditions, the weathering of such rocks, at or close to the water table with free movement of ground-water, is accompanied by the almost complete removal of certain elements, leaving a mixture mainly of aluminium trihydrate (as gibbsite) and limonite, together with the various resistant minerals originally present in the rock.

A satisfactory explanation of the origin of Sarawak bauxite must account for the fact that a thick bed of clay, which from its high silica content almost certainly contains kaolinite-type clay minerals, lies between the bauxite and the underlying fresh rock. Thick beds of kaolinitic clay commonly occur in such a position in other parts of the world. Some geologists have suggested that the formation of the clay was an intermediate stage in the formation of the bauxite, but that this is not necessarily so was shown by Gordon et al. (3, p. 140). The direct alteration of intermediate and basic igneous rock to bauxite is proved by the common occurrence of boulders composed of a core of fresh rock with a skin of bauxite, the transition taking place within 1 to 2 mm. On similar evidence, Harrison (10, p. 37) concluded that in basic igneous rocks weathering in a humid tropical climate "the mineral of first and direct formation from the plagioclase feldspars is gibbsite." However,

V. T. Allen (2) has established that under certain conditions similar igneous rocks alter directly to kaolinite-type clay minerals.

These differences in the primary products of weathering have been explained by Keller (11) by relating their formation to differences in pH at the surface of the parent mineral undergoing hydrolysis, the pH at the mineral surface being determined by the abrasion pH of the mineral and the pH of the ground-water. The term abrasion pH was introduced by Stevens and Carron (15) and is the pH that minerals develop when pulverized under water. If the pH of the hydrolyzing system is between 7 and 9.5, alumina is practically insoluble but silica is relatively soluble. Under such conditions, alumina is likely to remain as gibbsite, but silica will probably be removed in solution. If the pH of the system falls to between 4.5 and 7, both alumina and silica are only slightly soluble, and under such conditions are likely to combine as clay minerals.

The conditions necessary to give a hydrolyzing system with a pH of 7 to 9.5, such that bauxite would form, include the following according to Keller (11):

(a) Minerals in the rock with an abrasion pH of 9 or more. Minerals with such an abrasion pH occur in andesite, gabbro, and plagioclase amphibolite, the bauxite source rocks in Sarawak.
(b) Profuse rainfall to keep the solutions dilute and the concentration of silica below saturation point, and also to maintain at a minimum the concentration of carbonic and humic acids which, if present, would lower the pH and cause silica to be precipitated.
(c) High temperature to accelerate the hydrolytic reaction.
(d) An abundant microflora in the soil, such as occurs in a tropical climate, to consume humus and thereby reduce the concentration of humic acids in solution.
(e) High permeability of the rocks undergoing weathering, to permit the ground-water containing dissolved silica to escape.

Conditions producing a hydrolyzing system with a pH of 4.5 to 7, such that kaolinite would form, are most likely to occur below the water table, where the ground-water is likely to have a lower pH. As shown by Mohr and van Baren (12, pp. 289–290), this is mainly due to the fact that organic matter in the soil is broken down much less rapidly below the water table than in the better aerated soil above, causing the concentration of humic acids to increase (12, pp. 289–290). In addition, ground-water below the water table contains higher concentrations of dissolved salts, reducing the solubility of silica. The clays below the bauxite probably formed contemporaneously with the bauxite, but some clay might have formed at a later date, when the water table rose during the deposition of the alluvium that covers some of the bauxite.

Chemical evidence (Table 1 and Fig. 3) suggests that iron has been removed from the bauxite, but more data is required to discuss in detail this aspect of bauxite formation. The manner in which the iron was removed

is one of the most perplexing problems associated with the genesis of bauxite, and no satisfactory explanation appears to have been proposed. The conditions that have been postulated for the formation of bauxite are such that iron would be in the ferric state. Neutral to slightly alkaline conditions have also been postulated. Ferric iron, however, is soluble in notable amounts only if the pH is less than 3, and the great difference in the precipitation of ferric and aluminium hydroxides cannot therefore be the cause of the separation of these two hydroxides, as suggested by Rankama and Sahama (13, pp. 228–229). Possible methods by which the iron might have been leached are provided by the fact that ferric hydroxide readily forms colloidal solutions, and that humic complexes of iron form rather stable colloidal solutions.

GEOLOGICAL SURVEY DEPARTMENT,
KUCHING, SARAWAK,
Feb. 16, 1961

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SCIENTIFIC COMMUNICATIONS

MODIFIED FIELD METHOD FOR THE DETERMINATION OF NICKEL IN THE PRESENCE OF COPPER

V. G. HILL AND A. C. ELLINGTON

A rapid, yet simple method suitable for use by relatively untrained personnel was required for the determination of nickel in the presence of copper during a geochemical prospecting survey for nickel in the Blue Mountain Area of Jamaica, W. I. The usual dimethylglyoxime methods were unsuitable because copper also forms a colored complex with the reagent. The reagent α-furil dioxine recommended by Stanton and Cooper (7) is quite sensitive to copper, and the confined spot method developed in the U. S. Geological Survey Laboratories (4, 6, 8) requires the use of special apparatus that we do not have. Kalinichenko (2) recommended the use of sodium thiosulfate to complex copper, but in our hands this resulted in a marked decrease in sensitivity of the method. A variation of the dimethylglyoxime technique using a mercury-amino compound to tie up the copper, and sodium tartrate to tie up iron was worked out by us. If the amount of copper was excessive, and a copper-dimethylglyoxime was formed, this complex was decomposed by the addition of versene as suggested by Shean-Wei Kwauk (3). The method outlined below was found to be very satisfactory and met our requirements for a field method. An analyst, skilled in the method, can run approximately 160 samples in a working day.

Equipment

1 sample measuring spoon, 0.1 g capacity
15 doz Pyrex culture tubes, 19 × 150 mm
4 metal test tube racks to hold 40 test tubes each
3 wooden test tube racks to hold 15 test tubes each
2 Pyrex storage bottles—2 liters capacity
2 automatic pipettes, set to deliver 0.5 and 2.0 ml respectively
1 burette—25 ml capacity
1 electric water bath
pH paper
Whatman No. 41 filter paper

Reagents

1. Demineralized water
2. Isoamyl alcohol
3. Acid mix: Mix the quantities stated in the order given: HCl 400 ml, H_2O 400 ml, HNO_3 300 ml

4. Buffer: Dissolve 500 g sodium tartrate ($Na_2C_4H_4O_6 \cdot 2H_2O$) in 1,500 ml demineralized water. Add 150 ml ammonia previously saturated with mercuric iodide and filter through a Whatman No. 41 filter paper. Dilute to 2 liters. Check the pH after adding 0.5 ml acid mix to 2.0 ml of the buffer. The reading should be 8.5. Adjust if necessary.
5. Saturated dimethylglyoxime solution in alcohol.
6. Standard nickel solutions: Prepare a standard solution of nickel sulfate containing 0.958 g nickel sulfate per liter. 1 ml $\equiv$ 200 γ nickel. Dilute to suitable strength for standards.

Method

1. Measure approximately 0.1 g sample into the Pyrex test tubes with the measuring spoon.
2. Add 0.5 ml acid mix and digest in a boiling water bath for 45 minutes.
3. Cool, add 2.0 ml buffer and shake.
4. Add 0.5 ml saturated dimethylglyoxime solution in alcohol and shake.
5. Add 1.0 ml isoamyl alcohol and shake.
6. Allow the layers to separate.
7. Compare the color of the suspension in the upper layer with standards prepared by adding 0, 15, 30, 60, 120, 240 γ nickel to the test tubes and proceeding as from step 2 above. A gentle swirling action helps to homogenize the nickel dimethylglyoxime suspension in the organic phase and facilitates comparison.

RESULTS

Over 700 soil and laterite samples were analyzed by the technique described, and seven of these were re-analyzed by a laboratory method. In the latter method the samples were decomposed by treatment with nitric, hydrofluoric, and perchloric acid (5), copper and other heavy metals separated by a sulfide precipitation, and the nickel dimethylglyoxime finally separated by the method described by Chowdbury and Das Sarma (1). Volumetric glassware was used throughout the color developed measured with

TABLE 1

COMPARISON OF RESULTS BY PROPOSED FIELD METHOD AND LABORATORY METHOD

Distance along traverse	Concentration of Ni, in ppm					
	Field method					Laboratory method[2]
	Replicate values[1]				Average	
	A	B	C	D	Av	
0 ft.	300	300	300	300	300	610
200	150+	150+	150+	150+	150+	650
400	1,200	1,200	1,200	1,200	1,200	1,341
600	600	1,200+	1,200	1,200	1,050	1,128
800	2,400	2,400	2,400	2,400	2,400	1,941
1,000	0	150−	150−	150−	100	48
1,200	150−	150	150	150	150	12

[1] Replicate analyses of one sample.
[2] Analyst—Mrs. Joyce Luck.

a spectrophotometer at 530 mμ after standing for 30 minutes. The nickel content is interpolated from a standard curve.

The comparison of results from replicate analyses by the proposed field method with the laboratory method is given in Table 1. Figure 1 shows the distribution of nickel along a traverse as determined by both methods. The values obtained by the laboratory method are plotted as a solid line and those by the field method as a dotted line. Both curves have similar shapes, and they show that the proposed method is capable of detecting changes in the nickel content of soils and laterite and so is, suitable for use as a geochemical field method.

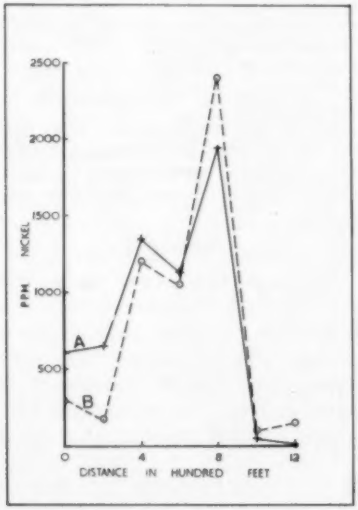

FIG. 1. Distribution of nickel values along a traverse as determined by laboratory method and proposed field method.

Discussion of Results.—The method appears to be simple, fast and accurate enough for use in a field laboratory even though the values obtained are in discrete steps of multiples of 15γ. Over the range 30–240γ nickel the precision is excellent and it is suggested that the size of the sample should be so adjusted that anomalous values fall within this range. Sometimes the lower and higher values might fall outside this range but all that is expected of a field method is to differentiate between samples from areas that deserve further study from those that do not, and this is precisely what this method was designed to do.

SCIENTIFIC RESEARCH COUNCIL,
KINGSTON, JAMAICA,
Mar. 20, 1961

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A SHORT REVIEW OF PERU'S MINERAL RESOURCES

W. C. STOLL

Petroleum.—There are three regions in Peru that have been productive of petroleum: the Pirin field near Lake Titicaca, the north coastal plain, extending from Tumbes south to Lambayeque, and the Oriente—the vast region east of the Andes, in the Amazon basin. The north coastal plain is the only important producer. It includes the old producing fields, Lobitos (1901), La Brea-Pariña (1875) and Zorritos (1863). At Lobitos and La Brea-Pariña oil is found in the Paleocene and Eocene, and production is obtained all the way from grass roots to depths of 8,000 feet. The Miocene is barren of petroleum in these concessions, but farther north, at Zorritos, the Miocene is the producing series. The strata have been intricately faulted in small blocks. Current production is in the neighborhood of 50,000 bbls per day for the whole coastal plain. The reserves are believed adequate for many years to come, but the rate of production is limited by the small flow—around 15 bbls a day average for 3,000-odd wells—maintained in part by water flooding and gas injection. No new large discoveries are at all likely in the region. A great deal of exploration in the Sechura desert to the south resulted negatively.

In the Oriente is a wide belt of concessions totalling some 10 million hectares, held by 15 companies. Exploration has been carried on, principally along the rivers, but nothing conclusive is yet known about the oil possibilities of this vast region. Two companies currently produce small quantities from the Cretaceous.

Coal.—The coal deposits include anthracite, bituminous and lignite. There are many deposits widely distributed in detached basins in the coastal and Andean regions, extending almost from Ecuador to Chile. Cretaceous anthracite is the most abundant; it extends in a belt 400 km long, west of

the Andean divide, through the departments of Cajamarca, Libertad and Ancash. The Santa field east of Chimbote is the most important. Here, the seams and enclosing quartzites are intensely crumpled. The mines produced for export for a few years after the second World War, but are now closed. Practically the entire bituminous coal output comes from the Goyllarisquizga mine of the Cerro de Pasco Corporation, which uses the output for making coke for lead smelting. Here the structure of the beds is simple, but the coal is extraordinarily high in ash and the reserves are depleted. Jatunhuasi, south of La Oroya, is the only other bituminous field of much promise. The Cretaceous Oyon coal measures, west of Cerro de Pasco at great altitudes, are reported to be extensive, but the beds are greatly folded and faulted. In the north of Peru, Tertiary lignite beds crop out in Tumbes and follow the coast as far as Piura. There is very likely a great deal of coal in the ground in Peru—estimates have ranged from a few to hundreds of billions of tons—but little of it appears apt for economical mining. The deposits are mostly remote, in regions of rugged topography and moderate to high altitude. The ash content is commonly high. With a few exceptions the bituminous coals are rather weakly coking. Mostly the geological structure of the seams is disturbed and complicated, which makes mechanical mining impracticable. Used as fuel, the cost per B.t.u. is too high.

Phosphate.—A couple of years ago oolitic phosphate rock in Miocene beds was discovered south of Piura, in the Sechura desert, near the sea coast. The deposits have been explored by a mining group. The phosphate-bearing area is some 100 kilometers long and 30 to 40 kilometers wide, and contains some thick zones of phosphate pebbles. The ultimate resources of this basin might ascend to some hundreds of millions of tons of phosphate rock. The discovery is of singular importance in a continent that urgently requires a wider and more intensive application of balanced fertilizers to its arable land. Fortunately Peru possesses large possibilities of sulfuric acid production, necessary to the making of superphosphate, mainly from its two large smelters.

Non-Metallic Minerals.—Among the non-metallic mineral output of Peru are included sand and gravel, limestone and marble, dolomite, diatomaceous earth, kaolin and common and refractory clays, as well as talc, pyrophyllite, barite and gypsum. Almost all common salt comes from the evaporation of sea water in pits.

Quaternary volcanic sulfur deposits occur in southern Peru. Those in the departments of Tacna and Moqugua may be large, but all are unexploited. In considering sulfur, a mention should be made of the large pyrite bodies at Cerro de Pasco and Morococha.

Borate (ulexite) deposits are known in Arequipa and Tacna in dry salt lake basins, in association with other salts and related in origin to vulcanism. The deposits of Laguna Salinas and Chillicolpa are believed important.

Guano.—The famous guano deposits are harvested as a renewable resource from 20 groups of coastal islands and 20 peninsulas, under the control of a government monopoly founded in 1909. This has managed to restore production by measures to conserve the birds and the anchovies on which

they feed. The present bird population is estimated at 12 million; formerly it has been as high as 40 million. The population waxes and wanes in accordance with long-term fluctuations of the atmospheric and ocean temperatures, which affect the depth at which the fish swim and consequently their accessibility to the diving of the birds. Thirty-seven kinds of birds inhabit the islands, of which the guanay (from which the term guano is derived) is the biggest producer. Production in 1956 reached a maximum of 336,000 metric tons; in 1959 it declined to 127,000 tons. The guano, rich in nitrogen, phosphoric acid and potash, is almost all consumed in Peru, where the demand exceeds the supply because a cheap official sales price is fixed. Peru is by far the largest consumer of fertilizer in South America. Fish-meal fertilizer is produced by many plants along the coast, and there is a factory for the production of artificial ammonium sulfate and nitrate.

Gold Placers.—The gold placers of southeastern Peru, in Puno, occur along the eastern slopes of the Eastern Cordillera as fluvioglacial deposits in basins at high altitude, as high stream terraces and river beds. They may be an extension of the gold placer region of northeastern Bolivia. Some have been worked since Inca and Colonial times, and are worked today by Indians with rude implements. In modern days a few small companies have worked from time to time, usually by hydraulicking. No dredges work in Peru, but plans for dredging on the Inambari river have been made by an American gold dredging company. In Puno the main deposits are San Antonio del Poto, Ancocalli and Aporama. Other placers are known in the adjoining departments of Cuzco and Madre de Dios. The resources of auriferous gravels are probably great, but their remoteness and inaccessibility, and the high altitudes and lack of water of some, have prevented their large-scale working so far. A smaller placer gold production comes from many rivers of central and northern Peru—the Pachitea, Iquitos, Marañon and other tributaries of the Amazon in the department of Loreto.

Vanadium.—Minasgragra (1) in Junin produced 99 million kilos of vanadium (2). It is now idle; present reserves do not exceed 10,000 tons of 1.75 percent V content. The deposit is composed of quisqueite, a lustrous hydrocarbon, and natural coke, together with masses of the vanadium sulfide, patronite. A secondary mineralization resulting from weathering consists of vanadates and vanadium oxides. The ore body is fissure-like and transects the enclosing beds of Cretaceous red shale. It has the form of a wedge or inverted cone which, at the surface, was lenticular in plan, measuring 350 by 28 feet. Downward, the deposit diminishes to a tail reaching a depth of 253 feet below the surface. The ore is cut by a porphyry dike. The mine yielded many thousand tons of a shipping products grading better than 6 percent V. There are many vanadium-bearing asphaltite deposits scattered through the Peruvian Andes. They are fissures or openings between beds, mostly lower Cretaceous limestones, filled with asphaltite whose V content ranges from 0.3 to 1 percent. Efforts to work these have so far been unavailing. The Minasgragra deposit is unique in respect of size, richness and some geological and mineralogical features.

Metallic Deposits.—The Santa Barbara quicksilver mine at Huancavelica

was the world's largest producer for 150 years. Cinnabar with minor native mercury and metacinnabar, occur as replacements in Cretaceous sandstone, as fracture fillings in Jurassic and Cretaceous limestones, and as veinlike ore bodies in fractures in Tertiary volcanics. The mineralization was associated with igneous intrusion following the main Tertiary deformation and volcanism in the Western Cordillera (3).

The Tertiary wolframite deposits of north-central Peru (Ancash and La Libertad) include the Pasto Bueno mines, which have been the most productive. They are shallow-seated, quartz-filled fractures containing wolframite, pyrite, sphalerite, tetrahedrite, enargite and galena, locally with arsenopyrite, marcasite, realgar and cinnabar. The veins show banding, coxcombs and druses. They show zonal relations with copper deposits (4).

Epithermal veins, chiefly productive of silver and gold, with lesser quantities of lead, zinc and copper, occur in the Miocene Tacaza volcanics of southern Peru, in Arequipa, Cuzco and Puno. They are fracture fillings, rich in silver at the surface. The silver minerals diminish in depth, but galena, sphalerite chalcopyrite and pyrite increase, together with the quartz and calcite gangue. The ores were apparently deposited close to an old Puna erosion surface. They generally play out at 200 to 400 m depth beneath the outcrops. Some important producers have been San Antonio de Esquilache, Palca and Cailloma (5).

Among the deeper-seated deposits is a dominant and historically most important type: the polymetallic deposits exemplified by Quiruvilca, Huaron, Cerro de Pasco, Colquijirca, Morococha, Casapalca, etc., occurring in a belt 100 km wide following the Western and Central Andes from Cajamarca south 600 km, at least to Huancavelica. These deposits contain mostly zinc, lead and copper, with more or less silver but generally little gold. They contain much arsenic and antimony, notably in enargite and tetrahedrite, and are likewise the source of bismuth, tin, cadmium, indium, tellurium, selenium and thallium, all recovered by efficient metallury at La Oroya smelter. The ores occur in a number of structural types—veins, massive replacements, pipes, disseminations—in association with Tertiary monzonitic stocks intrusive into many different Tertiary, Mesozoic and Paleozoic formations. They may exhibit zoning. The ratio of lead to zinc and the content of silver decrease with depth. Most mines of this kind are less than 300 m deep, and the depth expectations are at least twice as much. The blocked-out commercial ore reserves of all deposits of this type, including conservative estimates of "possible" ore, must be in the neighborhood of 35 million short tons.

A belt of porphyry copper deposits, including Cerro Verde, Toquepala, Quellaveco and Cuajones, extends southeastward from Arequipa to near the Chilean Border. They lie in the Andean dioritic batholith where it has been intruded by younger monzonitic bodies. The ore bodies occur in hydrothermally altered breccia chimneys, as deep blankets of secondary chalcocite beneath leached outcrops, and in relation to an old erosion surface now partly covered with volcanics. They contain molybdenum as well as copper, but generally lack lead, zinc, gold and silver. The published ore reserve

figures of Southern Peru Copper Corporation for its three great deposits are 1,100,000,000 tons with 1 percent copper. The mineralization is known to descend beneath the depths accessible to open pit mining.

Stibnite ore has been produced from more than 50 small mines, mainly in Puno, also in Huanuco and Lima. The individual deposits are said to be small. The Buena Suerte mine in Puno has probably been the largest producer. Peru is the only important South American source of antimony except Bolivia; most is now produced at La Oroya smelter, from zinc-lead-copper ores. Bismuthinite ore was produced for a time after 1905 at the San Gregorio mine. Bismuth output today comes from the treatment of flue dust at La Oroya, and this production led to the suspension of other bismuth operations.

A belt of quartz veins, formerly productive of considerable gold, follows the western slope of the Western Cordillera in southern Peru. The veins, enclosed in the Cretaceous Andean batholith, are narrow fracture-fillings of quartz with native gold and pyrite, which have been deeply oxidized. The average grade of ore did not exceed 10 grams per metric ton. Most ore terminated at depths shallower than 200 m. Another gold belt, probably older geologically, lies in the "Ceja de Montana"—the eastern slope of the Eastern Cordillera—in the department of Puno. These are quartz lenses with free gold and sulfides in Paleozoic slates. The Santo Domingo mine, from which extraordinarily rich ore has been produced from erratic shoots, is the best known representative of this class. Gold quartz deposits also occur in other parts of the Peruvian Andes. Those of the upper Marañon, especially the Pataz and Milluochaqui mines, were notable for their richness. Ore in the latter mine terminated at a depth of 200 m. Only four straight gold producers were working in Peru at the end of 1959. Others had closed down owing to low grade of ore or depletion of reserves. Peruvian lode gold prospects have low tonnage possibilities and mediocre grade—0.3 to 0.5 ounces per short ton.

Quartz veins with molybdenite have been worked near Jauja, department of Junin. One vein produced ore averaging 1 percent MoS_2.

The Antamina deposit, north of Cerro de Pasco, is a big body of fine-grained skarn with disseminated chalcopyrite and some sphalerite, molybdenite and scheelite. The Santander, west of Cerro de Pasco, near the continental divide, contains marmatite, galena, and chalcopyrite in a garnetite gangue. In the south, in Cuzco and Apurimac, is a northwest-trending belt of contact-metasomatic chalcopyrite deposits (Tintaya, Ferrobamba, etc.) where Cretaceous limestone is penetrated by small granitic bodies (6). Here are likewise many contact deposits of magnetite and hematite replacing limestone.

The large Marcona iron ore deposits on the coast of Ica are believed to have been formed by the replacement of dolomitic limestone of the Paleozoic Marcona formation, in relation to the intrusion of granite. Ore production until May 1960 totalled 18,200,000 long tons with grade around 60 percent iron. The total reserves may reach 600,000,000 long tons, including low-

grade ore suitable for beneficiation. The Acari iron deposits, 60 km east of the port of San Juan, are magnetite-hematite veins in diorite.

In the Eastern Cordillera of central and southern Peru serpentine bodies have been discovered, some of which contain chromite deposits of as yet unknown importance.

Small occurrences of manganese ore, and of nickel and cobalt minerals in small veins, have been reported, but nothing certain is known respecting their genetic classification or commercial importance. The famous Bolivian tin belt does not appear to penetrate into Peru.

The gross value of all Peruvian mineral production in 1958 was about 5 billion soles (roughly $221,000,000), of which metals (including the metal content of ores, mattes, alloys, etc.) accounted for about 62 percent, crude petroleum, 29 percent, and coal and non-metallic minerals 8.6 percent. Mining accounts for approximately 11 percent, and petroleum 4 percent of the national income. The exports of metallic and non-metallic mineral products during 1957 had a value of 39 percent of the value of the country's total exports. If petroleum exports are taken into account, minerals as a whole accounted for about half Peru's exports. The minerals industry employs 55,000 persons, or about 2.5 percent of the economically active population. The number directly relying on the industry for a livelihood may be around 300,000. The minerals industry employs comparatively few people, in proportion to the value of output, because it is efficient and highly capitalized.

From the world industrial and strategic viewpoint, Peru contains important ore reserves of copper, zinc, lead, silver and some of the rarer metals, as well as of iron ore.

The data here presented were gathered in 1960 during a brief field study in Peru, which included visits to many principal mines, metallurgical plants and oil fields, and conversations with engineers and geologists active in mining, both in industry and the government, all supplemented by a partial review of the available publications on the country's mineral resources and geology.

LIMA AND ARGENTINA,
March 26, 1961

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AN UNUSUAL OCCURRENCE OF MOLYBDENITE, IN A MANGANESE MINE, IN TAILEVU PROVINCE, FIJI[1]

M. J. RICKARD

A specimen of epidote from a small manganese mine in eastern Viti Levu, handed in by a prospector (R. C. Singh) was found to contain molybdenite. The mineral was first identified by J. N. Monro of the Mines Department, Suva, and was confirmed by chemical tests at the Geochemistry Department, Imperial College, London, and the Bureau of Mineral Resources, Australia. This assistance is gratefully acknowledged.

The specimen came from a small open-cut manganese mine 600 yards south-south-east of the Wainivesi zinc-copper mine which is shown on the regional geological map (1). The location of the manganese is controlled by the intersection of a small fault with a marble-diorite contact. The molybdenite is scattered throughout yellow epidote patches in a small lump of hard manganese ore.

The geological setting is not unique, but this is the first record of molybdenite in Fiji; this fact and the unusual association with manganese and epidote are considered noteworthy.

Geological Setting.—Several thin limestone bands occur in argillites and volcanics of the Lower Miocene Wainimala Series and these are cut by dike-like basic to intermediate (gabbro-tonalite) plutonics (1). Base metal (zinc, copper, iron) mineralization is associated with plutonic intrusion and the limestones commonly act as favorable hosts.

At the Wainivesi manganese mine a steeply-dipping fine quartzite and coarse marble band, striking N–S, are sheeted by a plutonic dike. The latter is deeply weathered and highly altered, but small feldspar phenocrysts and a few chloritized ferromagnesians can be seen in the clayey matrix. Although quartz is usually weather-resistant none was seen and it is therefore assumed that the plutonic rock is a diorite.

Apart from a few thin dark bands the light gray-white marble is very pure. By comparison with other limestones in this district its coarsely crystalline texture is obviously due to recrystallization during the diorite emplacement (Houtz, pers. comm.).

The quartzite is strongly hematized in the vicinity of the manganese ore and lumps of hematitic quartzite in the manganese near the faults contain disseminated pyrite.

The genesis of manganese ore in Fiji is generally considered to be that of residual concentration. In this case a 25 feet wide "vein" of massive manganese ore (pyrolusite and psilomelane) follows a small fault that cuts the marble within the diorite (Fig. 1). The marble is only 10 feet wide in the quarry but it thickens rapidly along strike. The manganese replaces the diorite, the fault breccia, and the marble. Except for the marble where contacts are very sharp, the manganese boundaries are irregular and diffuse, and manganese spotting extends out into the diorite.

[1] Publication authorized by Government of Fiji.

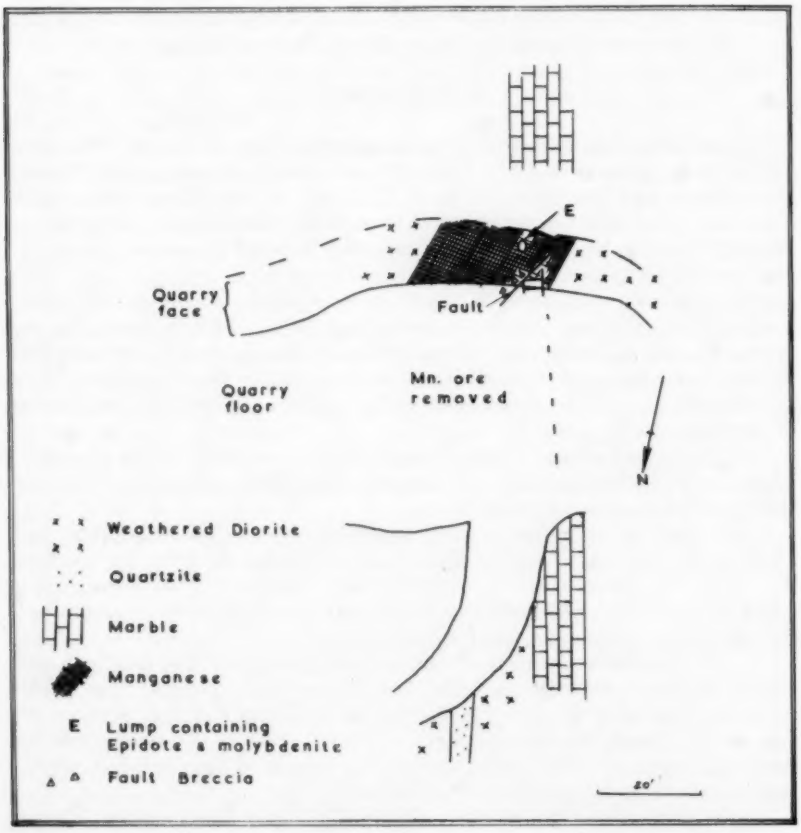

FIG. 1.

Epidote was found at one place only; it occurs as small lenses and spots in an 18 by 12 inches lump of hard psilomelane (the third dimension cannot yet be determined). This lump is completely within the manganese ore and although close to the marble is separated from it by the fault. The epidote is a dull, yellow color and massive to finely crystalline. Houtz (1) records epidote with magnetite from this area but although magnetite boulders were seen in several places along the strike no epidote could be found to check for molybdenite.

Mineral Relations.—The molybdenite occurs as tiny flakes, the largest of which is 1 mm across, in the epidote. Chemical analysis showed 0.29% molybdenum in the epidote rock but its concentration is very variable. (Analysis by A. J. McDonald of Imperial College using zinc dithiol method.)

The boundaries of the epidote patches are very irregular and the epidote is obviously being replaced by psilomelane.

Under the microscope the epidote is seen to consist of a fine and medium grained patchy crystalline mozaic. It is generally colorless but small patches show the typical yellow pleochroism. An important feature is the absence of the reddish manganiferous epidote piedmontite.

Clusters and strings of small yellow siderite granules occur within the epidote and also in veinlets in the magnetite boulders.

The hard (5–6) manganese mineral with the epidote was shown to be psilomelane by simple chemical tests. A polished section, however, shows two manganese minerals and a complex replacement texture. The manganese penetrates along cracks, small veinlets spreading out and replacing the epidote. In places it is crystalline, presumably pseudomorphing epidote.

The molybdenite occurs as thin curved plates and has normal optical properties. It is mostly restricted to the epidote but an occasional flake is seen in the psilomelane. The texture suggests that the molybdenite was originally in epidote and that it resisted replacement by manganese.

A sample of weathered diorite was disaggregated and the heavy minerals separated in bromoform. Magnetite, ilmenite, limonite, felspar, apatite, zircon, pyrite and chalcopyrite (?) were recognized but there was no molybdenite. The marble also contained no molybdenite but a few doubtful flakes were seen in the hematized quartzite.

Discussion.—Molybdenite is generally associated with granitic rocks, either as disseminations in the granite, or concentrated at the margins in "late stage" veins. The presence of molybdenite is an unusual feature for any manganese deposit, and disseminated pyrite has never been found in Fijian manganese mines.

This occurrence is unique in several respects, but the association with manganese, at least, can be ruled out as fortuitous. The obvious late replacement of earlier formed rocks and minerals and the lack of other manganese minerals, especially piedmontite, suggests that the manganese was deposited at a later stage. Probably the intersection of the small fault with the limestone provided a favorable location for deposition and concentration of residual manganese as is generally the case in Fiji.

Thus is can be argued that the introduction of molybdenite and possibly pyrite was probably associated with the intrusion of diorite. This explanation does not, however, account for the restriction of molybdenite to the epidote rock in preference to the marble and diorite.

Molybdenite has not been found elsewhere in Fiji but there is a large central plutonic complex, as yet unexplored, and a search for this valuable mineral will be made during regional mapping.

GEOLOGICAL SURVEY DEPARTMENT,
SUVA, FIJI,
April 1, 1961

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DISCUSSIONS

CONDITIONS FOR ILMENITE ALTERATION

Sir: In his recent discussion of conditions for alteration of ilmenite, Ralph Austin (1) gives an excerpt from a letter to me in which he postulated that much of the alteration of sand ilmenites took place below the zone of weathering, under reducing conditions. To make it clear that I am not in complete agreement with this view, I would like to quote from a letter to Mr. Austin dated February 9, 1960, in which I made the following comments:

"Your postulation . . . may well be valid for explaining the anatase and pyrite clusters in the Westwater sandstone. However, for this mechanism to be accepted as applicable to sand ilmenites generally, it would be necessary to explain the high ferric iron content of sand ilmenites. Although this might be attributed to subsequent weathering, Cannon (2) reported that the TiO_2 content and degree of alteration of ilmenite in Florida sands decrease with depth, especially below the water table, indicating that the alteration was accomplished mainly in the weathering zone, at the present location of the deposit.

It is of course probable, as you point out, that deposition, erosion, and subsequent redeposition could occur several times in the course of transport of individual grains."

I certainly agree that in sediments rich in organic matter, the concentration of humic acids and sulfur would be many times that in rain water, and in my forthcoming paper (3), to which Mr. Austin referred, statements emphasizing the importance of acid concentration are made: . . . "Ground water is likely to contain traces of sulfuric, nitric, and hydrochloric acids, and when organic matter is present . . . humic acid. . . . The pH of the weathering solution is . . . a most important factor in determining the rate of weathering. Measurements of the pH of ilmenite-bearing soil should give a good indication of the rate of weathering of ilmenite in specific locations."

If the sandstones discussed by Mr. Austin did originally contain ilmenite, then the fact that no ilmenite was found shows that alteration was considerably more severe than in the case of sand ilmenites, where residual unaltered ilmenite is easily identifiable. It seems to me that the presence of ferric iron, and lower intensity of alteration in New Jersey and other sand ilmenites is good evidence for a different alteration environment than that which prevailed in the case of the "vanished ilmenite" of Ambrosia Lake.

LANGTRY E. LYND

NATIONAL LEAD CO.,
S. AMBOY, N. J.,
March 10, 1961

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KOLAR GOLD FIELD, INDIA

Sir: The November 1960 issue of Economic Geology contains a paper entitled "Structural control and localisation of gold-bearing lodes, Kolar Gold Field, India" by S. Narayanaswami, Mohammed Ziauddin and A. V. Ramachandra, three members of the Geological Survey of India who have carried out an intensive programme of geological mapping on the Kolar Gold Field. On page 1433 the authors state "it is now possible to predict the structural pattern and behaviour of lodes in any part of the Field"; on page 1444 they say "the remarkable stratigraphic control exhibited by the lodes forms a foolproof guide for their correlation from mine to mine and also to trace their outward extension beyond the present mining limits"; and on page 1450 the authors leave the reader with the impression that the Kolar oreshoots are controlled and localised by folds.

The Kolar Gold Field is one of the classic examples of a mining field where important oreshoots show a broad pattern as they occur and recur along the strike and down the dip. Nevertheless, despite all the underground work which has been done during three-quarters of a century, from the standpoint of the mining engineer concerned with the detailed exploration of the mines and with the discovery of new oreshoots, it is correct to say that there still exists no foolproof guide for the correlation of lodes from mine to mine; that more gold has been won from straight parts of the lodes than from where the quartz occurs in so-called "folds"; and that there are far too many puzzling anomalies for it to be considered that the problem of the conditions controlling the deposition of the oreshoots has yet been solved.

The authors of the paper have paid the writer of this letter the compliment of saying that his paper of 1924 is still the best description of the underground geology of the Kolar Gold Field, but I am impelled to make the above correction to the views expressed by the authors because Economic Geology is widely read by those engaged in teaching economic geology, and it is important in the interests of scientific accuracy that it should not be assumed that the geological work done on the Kolar Gold Field has as yet provided sufficient understanding of the conditions controlling the depositions of ore to enable valid predictions to be made.

T. Pryor

c/o The Institution of Mining & Metallurgy,
44, Portland Place, London,
March 10, 1961

POSTDEPOSITIONAL ALTERATION OF SANDSTONE MINERALS UNDER ACIDIC REDUCING CONDITIONS: A FACTOR IN THE INTERPRETATION OF SANDSTONE TEXTURE

Sir: Recently Dorothy Carroll (3) has drawn attention to the alteration of ilmenite in sand sediments buried under reducing conditions and suggested that where pyrite and siderite occur in sands reducing conditions may have played an important part in the alteration of other iron bearing detrital minerals such as garnet and amphiboles. Austin (2) confirmed the importance of such processes, briefly describing Jurassic sandstones in which authigenic kaolinite, pyrite and anatase extensively replaced detrital feldspar and magnetite. He suggested that the changes were brought about during a single period of postdepositional alteration in an acidic, reducing environment.

Preliminary investigation suggests that such processes have been important in producing the typical texture of subgraywacke sandstones in the Namurian of south-west Derbyshire, England. Thin sections of these rocks show K-feldspar deeply corroded and replaced by kaolinite. In some coarser varieties large detrital garnets are fissured and partly replaced by the clay that forms the general sandstone matrix; zircon and tourmaline appear to be unaltered. Clots of a black opaque mineral have developed at the expense of detrital biotite and may make up 15 percent or more of the rock. Binocular examination of heavy residues confirms that much of the opaque material is aggregated with biotite and chlorite. Magnetic separation yields a very small fraction of fine magnetite but the bulk of the opaque material is probably poorly crystallized pyrite. Finely divided secondary siderite is abundant in some beds. Detrital ilmenites are deeply leucoxinized.

Double staining of HF-etched thin sections with methylene blue and sodium cobaltinitrite clearly brings out the relationship between clay in the rocks and highly or completely altered K-feldspar. Where it pseudomorphs the feldspar the kaolinite (dickite?) is commonly well crystallized showing the vermicular habit described by a number of workers: the clay not directly replacing K-feldspar in situ—the truly interstitial matrix—is less well crystallized and was probably deposited by pore solutions bearing alumina, silica and iron derived from the breakdown of feldspar and biotite. The true secondary nature of this clay is demonstrated by the way in which it replaces —in places extensively—the edges of detrital quartz grains and tends to destroy the slightly flattened or very slightly concavo-convex contacts between quartzes.

If, as these observations seem to indicate, the majority of clay in these rocks has been generated by postdepositional alteration of feldspar under the conditions postulated by Carroll and Austin, then such alteration processes must be highly significant in any general discussion of textural maturity in sandstones. Smithson (5) demonstrated the relationship between authigenic dickite and intrastratal solution of heavy minerals in some English Jurassic

sandstones. However, to the writer's knowledge only Potter and Glass (4) have given any consideration to the possibility that secondary clay that has developed at the expense of detrital non-clay minerals may complicate common environmental deductions based largely upon the clay content of sandstones. A high clay content need not necessarily indicate poor sorting by sediment transporting currents or at the site of deposition. Where a mineralogically immature sediment is concerned abundant clay may rather reflect the pH/Eh conditions of burial.

The Namurian sandstones of Derbyshire are commonly regarded as non-marine deltaic deposits, though Allen (1) has suggested a marine origin for one group of beds with abundant evidences of turbidity current deposition. Both clay-rich and clay-poor feldspathic sandstones are common in the Namurian of Derbyshire and it seems possible that the clay-rich subgraywacke type may indicate deposition under stagnant, highly acid and reducing conditions whilst the essentially clay-free gritstones accumulated in shallow, better aerated water with a somewhat higher pH and possibly positive Eh.

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IRON FORMATIONS IN THE SOUTHEASTERN UNITED STATES

Sir: I have read with interest the suggestion in this JOURNAL by Mr. J. E. O'Rourke,[1] that there is a similarity between the Precambrian banded iron ores and the iron ores found in the southern Appalachians. Surely Mr. O'Rourke must have been misled by the overly exuberant reports made by geologists over 100 years ago. In many of those older reports, the authors were attempting to promote mineral deposits in the southeastern United States, and specifically those in their own states. I am certain that an examination of a number of more recent reports of these same deposits of iron in the southeastern United States would reveal a picture quite different from that set forth in Mr. O'Rourke's paper.

1 O'Rourke, J. E., 1961, Paleozoic banded iron-formations: ECONOMIC GEOLOGY, v. 56, pp. 331–361.

Mr. O'Rourke considered a number of examples of sedimentary iron deposits in the Appalachians other than the Clinton type. He considered that these ores are either conventional iron-formations, or a closely related variety. Iron-formation was defined by O'Rourke (p. 332); "The term iron-formation is used in this report only for sedimentary iron-ores that show alternating bands of iron minerals and cryptocrystalline silica (or 'chert')." According to this definition, iron-formation is yet to be found in the southeastern United States. Having studied and reported on Precambrian iron-formations (8), as well as having examined and reported on iron deposits in nine southeastern states (9), I suggest that about the only similarity between the iron ores of the southern Appalachians and the Precambrian banded iron-formations is that they both contain iron.

The non-Clinton iron deposits of the southern Appalachians were grouped by O'Rourke (p. 350) into: a) Cambrian deposits of the Valley and Ridge province, and b) a belt of deposits in the "Paleozoic (?)" rocks of the southern Piedmont. First, the mineral deposits to which he refers as being examples of conventional iron-formations do not resemble the Precambrian formations in mineralogy, lithology, texture, or in any other important diagnostic feature except for the presence of magnetite or hematite. Secondly, in all cases mentioned except for the Cartersville district, the Paleozoic age is doubtful; in this case, where the Paleozoic age was certain, Mr. O'Rourke placed the layer of iron ore in the wrong formation. Surely these features do not suggest the presence of Paleozoic banded iron-formations in the southern Appalachians. Let us consider a few examples used by Mr. O'Rourke.

The first example offered for the Valley and Ridge province was the gray iron ores near Talladega, Alabama. Ignoring for the moment the fact that this area is on a boundary between two provinces, I suggest that the age of this quartzite has not been proved. Although in some places a quartzite that resembles the one at Talladega is Cambrian in age, statements that this non-fossiliferous quartzite is the Weisner, and that the Weisner is the base of the Paleozoic for "the entire length of the southern Appalachians" (p. 351), is speculation and is still unproved. As to the iron deposits: Reed (1949), showed that they are not banded iron-formations; but instead are ferruginous meta-sandstones repeated in many places by folding and faulting.

The example used for banded iron-formations in the Cartersville district draws upon the recent paper by Kesler (6). O'Rourke states that in the Cartersville district, gray ores, ". . . are said to be interbedded with quartzites and slates of the Weisner formation (44) and with dolomites of the overlying Shady formation (28)." The (28) refers to Kesler's paper, and the (44) is McCallie's work which Kesler not only reviewed, but corrected. Kesler states: (p. 10), "McCallie collected fossils from bedded specular hematite at the Roan Mine and erroneously reported that they were from the Weisner formation. The hematite is now known to be a part of the Shady formation, and Resser has identified the fossils with the Shady fauna." There is no need to repeat McCallie's observation. Even so, these deposits in the Shady in most features are unlike the banded iron-formations of the Lake Superior district, although they have more features diagnostic of Pre-

cambrian iron-formation than do the other deposits mentioned by O'Rourke for the southeastern United States.

The reference to the "hard, dense, specular ore of steel-blue color" (1869) strung out along the Tennessee-North Carolina border in Cambrian clastics is so old and vague, that little should be said about it. W. S. Bayley, a man who contributed significantly to the understanding of Precambrian iron ores (1, 2), reexamined this area in question. I could find only one time that he noted a similarity between these ores and Precambrian ores. In that place he stated (2, p. 22) that some of the specular hematitic-magnetite ore in Carter County, Tennessee resembled the more massive specular ores of the Marquette district. The formation in which this ore was found is supposedly the Cranberry granite (gneiss). Though the minerals resemble one another, the formations do not.

In the Piedmont province, there are indeed a great number of hematite and magnetite deposits. Some of these originated by replacement, some are hydrothermal, some are sedimentary, and most have been metamorphosed. The age of each must yet be established.

The examples cited for Alabama and Georgia are clearly in rocks of unknown age. As Crickmay (4, p. 1392) stated for the rocks of lower Talladega age: "Much of the evidence favoring a Paleozoic age for the series is based upon opinion rather than upon fact, and some of this evidence has been misinterpreted." Furthermore, these are not banded iron-formations.

Surely we expect one day to be able to identify Paleozoic sediments in South Carolina. Until that time, the formations that were identified over 100 years ago, should be left with a questionable age. This "nearly continuous iron ore belt that extends across North Carolina into Virginia," as quoted from Nitze (1891), simply does not exist. The discontinuous pods of magnetite and hematite, which may be found in the Piedmont, are not sedimentary iron-formation; they may have been layered by metamorphism, but not banded by rhythmic interlayering of chert and iron silicates or iron carbonates.

According to the most recent literature on the Mount Athos formation in Virginia, Brown (3, p. 79) does favor a sedimentary origin for the ores; however, he notes that Furcon (5, p. 98), who studied the ores in detail concluded they were hydrothermal. Thus in addition to not resembling the Precambrian iron-formations, the age for these rocks is uncertain, and their origin is questionable.

Mr. O'Rourke states (p. 352), "Traditionally, the rocks of the piedmont have been considered 'Precambrian' but after repeated discoveries of fossils, some as young as Carboniferous (21), they are now regarded largely Paleozoic." To put it mildly, this is a complete overstatement of the facts. I wish we could find fossils in rocks of the Piedmont with the ease implied by O'Rourke. The example he cited was for a fossil recognized in 1941 in a boulder reported from a rock sequence which had been accepted by the Alabama Geological Survey long before as partly Paleozoic on the basis of fossil and structural evidence. Thus, his example suggests only that twenty years have passed since a fossil was found in members of a rock sequence

known to be fossiliferous. Surely this does not suggest "repeated discoveries." As a matter of fact, it suggests to me a paraphrase of an old Carolina statement applied to the Piedmont: "It's a long time between fossils."

Thus, I am certain that when Mr. O'Rourke completes his review of modern literature on iron ores of the southeastern United States, and examines the deposits directly, he too will find it difficult to locate Paleozoic banded iron-formations in this region.

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REVIEWS

Geology of Ore Deposits (Geologiya Rudnykh Mestorozhdenii). Academy of Sciences of the USSR. September–October, 1959; Vol. 1, No. 5 (in Russian).[1]

N. S. Zontov, The Geological Structure of the Copper-Nickel Deposit of the Northern Part of Rudnaya Mountain (Noril'sk Region) (Pp. 3–20).

The deposit is located in the northwestern part of the Siberian platform. The stratigraphic sequence of the area consists of Devonian, Middle Carboniferous, and Permian formations. The Permian period was characterized by trapp vulcanism. Three lava horizons formed during the Triassic. An intrusion of ore-bearing differentiated gabbro-diabases followed the second Triassic lava series. The ore-bearing intrusions are contemporaneous with the folding and penetrated into the intraformational decollement-type fractures. The structural control of the intrusive bodies depends also on the mechanical properties of the layered rocks and acquires therefore an aspect of stratigraphic dependence. The syngenetic ore bodies are located at the footwall of the intrusions, while the postmagmatic ore veins penetrate into the underlying rocks. Some ore is also disseminated in the wall rocks. The gabbro-diabase intrusion is 650 m long and 270 m wide. It is located in the axial part of a syncline with limbs dipping at 20°.

High-grade disseminated ore forms trains striking southward from each ore lens. The flow of sulfides within the liquid magma had a northern direction along the inclined bottom. The northern depression in the bottom acted as a trap. The separation of sulfides from magma was the result of liquation during the magmatic stage. This is indicated by the sideronitic texture, by the local lamination of sulfides within the disseminated inclusions, by the accumulation of sulfides at the bottom of the intrusion where no fracturing existed, and by the replacement of silicates by sulfides. There is no wall rock alteration. The pyrrhotite veins fill the flat-lying fractures, whereas the steeply-dipping veins, which are parallel to the axial planes of the fold, consist of chalcopyrite ore. The size of chalcopyrite crystals and the amount of pyrrhotite decrease with depth. The deepest horizons consist exclusively of chalcopyrite and pentlandite.

The flat-lying veins formed in fractures that originated due to tension in vertical direction. These fractures tapped the bottom part of the intrusion where the sulfides were still liquid. The steeply-dipping fractures could open only in areas where local folds were formed. The residual solution from the flat-lying veins penetrated downward into the underlying rocks after the crystallization of pyrrhotite. The tapering off of the chalcopyrite veins with depth indicates that no ore can be expected at deeper horizons.

L. S. Borodin, Perovskite Mineralization in the Vuoriyarvi Massif (Pp. 21–30, 8 plates).

The North Karelian Vuoriyarvi massif is emplaced in Archean granite-gneisses, and occupies an area of 18 square km. The central part of the massif

[1] Regular preparation of reviews of this journal is supported by a grant from the National Science Foundation.

contains coarse crystalline phlogopitized pyroxenites with titanomagnetite and perovskite. The ore minerals form disseminated zones, schlieren, or thin veinlets in phlogopitized pyroxenites.

The perovskite mineralization was preceded by granulation of the coarse crystalline phlogopitized pyroxenite. Perovskite is absent in areas where no granulation occurred. There is a direct relation between the abundance of phlogopite and the accumulation of perovskite. Perovskite forms aggregates and veinlets cutting across phlogopite crystals and indicates a direct relation to the final stages of phlogopitization. Very convincing is the replacement by perovskite of ilmenite lamelli included in magnetite. Some crystals of perovskite have zones of growth and push apart the surrounding minerals. The marginal zone of the pyroxenite core is enriched in apatite. The association of perovskite mineralization with the process of alkaline metasomatism confirms the affiliation of perovskite and carbonatite deposits with the massifs of complex ultrabasic alkaline rocks.

A. V. Korolev, S. T. Badalov, Primary Mineralization Zoning in the Ore Field of Almalyk (Pp. 31–38).

The area under study occupies about 30 square km in the lower reaches of the Almalyk and Nakpai rivers in Uzbekistan. The country rocks consist of pre-Givetian quartz porphyries overlapped by Upper Devonian carbonate formations. All these rocks are intruded by Early Variscan monzonites, Late Variscan granite porphyries, and dikes of different composition. The zoning in the distribution of ore deposits depends on the Late Variscan tectonic movements. The hydrothermal veins are accompanied by a higher content of copper and zinc in the country rocks.

The distribution of ore deposits in the Almalyk ore field follows a roughly concentric pattern. The central part is characterized by copper-molybdenum deposits of the porphyry copper type. The gold deposits formed within monzonite some distance from the central zone. The marginal zones are represented by lead-zinc deposits in carbonate rocks. The capacity of rocks to shatter is another local factor contributing to mineralization. The location of copper-molybdenum deposits near the intrusive stocks depends on tectonic and lithologic factors in the zoning. The repeated tectonic fracturing was accompanied by a regular change of the ascending ore solutions. The vertical and horizontal changes of mineralization in some deposits during the flow of hydrothermal solutions may be the result of the mixing of hydrothermal solutions with vadose waters. The primary zoning in the Almalyk region is the result of several factors that have a direct bearing on the methods of prospecting and exploration.

T. N. Shadlun, Some Regularities in Metamorphism of the Pyritiferous Lead-Zinc Deposit of Tekeli (Pp. 38–56, 10 plates).

The deposit is located in the Dzhungarian Alatau Range, in Kazakhstan, and is represented by a complex bedded ore zone in Upper Silurian and Lower Devonian carbonaceous cherty and calcareous slates interbedded with limestone or dolomite. The author studied the textural and structural features of ore in thin and polished sections. The study was supplemented by spectral and chemical analyses. The ore consists of pyrite, sphalerite, galena, quartz, calcite and dolomite. The ore and the country rocks are characterized by the abundant

dissemination of microscopic spherulites of pyrite (partially by melnikovite[1]), ranging in size from 1 to 39 microns, associated with finely dispersed graphite and fragments of carbonaceous substance. Pyrite and carbonaceous matter commonly form bands that are conformable to the bedding. There are also finely banded and crenulated beds of massive pyrite ore. Large pyrite metacrysts, which include spherulites, formed during the process of cumulative crystallization. In contrast to pyrite of hydrothermal origin, these pyrite crystals have no zoning. Some zoning is present in pyrite associated with galena and sphalerite ore. Pyrite contains As, Cu, V, Ti, Ge, and Ni (thousandths and ten thousandths). All these elements are present in similar amounts in the carbonaceous cherty slates, except V and Ti which occur in slates in amounts ten times higher than in pyrite. The author concludes that the silisification and dolomitization were not of hydrothermal origin.

Bands enriched in sphalerite and galena of hydrothermal origin were superimposed over the pyritized rocks. Later, dynamometamorphism altered the texture of ore. The finely-banded pyrite ores associated with the carbonaceous cherty slates are evidently of syngenetic origin. Pyrite formed during the diagenesis and metamorphism of banded sediments containing organic matter. The banding and schistosity contributed to the deposition of hydrothermal metasomatic sphalerite and galena in the rocks. The absence of sericite in pyrite ores and in pyritized rocks indicates their non-hydrothermal origin. There is a great similarity between the ores of Tekeli with those of Rammelsberg.

B. V. Brodin, The Mineral Composition and the Distribution of Mineralization in the Kurgan District (Talassky Alatau) (Pp. 57–73).

A group of cassiterite-sulfide and base metals deposits of the Kurgan district is located in Kirghizia. The country rocks consist of Cambrian and Ordovician metasediments intruded by syenites. The ore bodies form complex pipes. The age relationship of mineral associations in different deposits of the area indicate that there were five stages of mineralization. The flow of mineralizing solutions was intermittent and renewed each time when fractures formed. The change in composition of ore solutions during each consecutive stage is indicated by the deposition of different mineral associations. Deposits with the following principal mineral formations are described: (1) Cassiterite-sulfide formation with considerable galena, pyrrhotite, sphalerite (marmatite), pyrite, and marcasite. The gangue is quartz with some siderite. (2) A similar mineral association, but with different ratio of minerals and siderite gangue. (3) Banded ore consisting of marcasite and pyrite and dark brown sphalerite. (4) Massive metasomatic pyrrhotite ore with some pyrite, irregular inclusions of chalcopyrite, sphalerite, and in places galena with fluorspar. The marginal parts of these ore bodies are represented by the porphyry type of mineralization. The consecutive appearance of magnetite, followed by arsenopyrite, pyrite, and pyrrhotite, and the deposition of stannite and franckeite, instead of cassiterite, indicate the evolution of the hydrothermal solutions, which become more reduced. This may be explained by the decrease of temperature resulting in an increased dissociation of hydrogen sulfide. The horizonal and vertical zoning around the syenite massifs is represented by the appearance of later stages of mineralization farther away from the syenite massifs of presumably Variscan age. These features are a major criterion in guiding the exploratory work in other regions of the Tien Shan Mountains.

[1] Variety of iron disulfide.

R. V. Karpov, Pegmatites of Basic Rocks in Monchetundra and the Associated Sulfide Mineralization (Pp. 74–90).

The Monchegorsk nickel-bearing differentiated pluton of the Kola Peninsula is of Middle Proterozoic age and occupies an area of 50 square km. The copper nickel deposits of the region are represented by massive ore and porphyry type of ore. The ore consists predominantly of pyrrhotite with areas enriched in chalcopyrite. In places it consists of pure pentlandite. Magnetite with pyrite predominates in vein apexes and are the result of oxidizing reactions at the end of the mineralization process.

An elaborate petrographic study of rocks and their chemical analyses indicate that various pegmatitic and pegmatoidal mineral formations of a composition close to that of the parent rocks are characterized by extremely large crystals, regular mineral intergrowths, enrichment in accessory minerals and minerals containing H_2O, P, F, S, and CO_2, by metasomatism, and in places by zoning of minerals. The pegmatoidal formations and the sulfide copper-nickel ores are crystallized evidently during the last stages of massif formation. The alteration of composition of the pegmatite from basic to more acidic corresponds to an increase in the nickel to copper ratio in associated sulfide ores. The Ni : Cu ratio in bornite-chalcopyrite mineralization of the early gabbro-pegmatite dikes is 1 : 30 to 1 : 50. The Ni-Cu ratio in pentlandite-pyrrhotite veinlets associated with the diorite pegmatite is 5 : 3. Finally, the Ni-Cu ratio in pyrite-pentlandite-pyrrhotite ore bodies associated with the plagiogranitic pegmatites is 8 : 1. There is an increased amount of phosphorus and fluorine (presence of apatite) in bornite-chalcopyrite ore, while the formation of the pyrite-pentlandite-pyrrhotite ores was accompanied by the activity of water and carbon dioxide which produced strong wall-rock alteration.

Yu. V. Kazitsyn, G. V. Aleksandrov, The Metasomatic Zoning During Argillitization of Granite-Porphyries near the Ore Bodies (Pp. 91–103).

The argillitization was studied as a characteristic hydrothermal wall-rock alteration of a rare metal occurrence in the Eastern Transbaikal region. The country rocks consist of biotite porphyritic granites of Paleozoic age intruded by Upper Jurassic granitoids accompanied by dikes of diorite porphyry, granite porphyry, and aplites. The mineralization is associated with silicified breccia. There are six zones surrounding the ore body: (1) Unaltered granite porphyry; (2) zone of weak carbonatization, attaining a thickness of 20 m, characterized by the replacement of hornblende by carbonate and by the leucoxenized sphene; (3) zone of sericitization (replacement of plagioclase by sericite (hydromica and kaolinite); the subzone (3a) contains biotite and more sericite than kaolinite; subzone (3b) is characterized by chloritization and an increased amount of kaolinite; (4) zone of predominant kaolinization, where all orthoclase is replaced by kaolinite-chalcedony aggregate; (5) zone of total kaolinization and silicification (complete absence of sericite and chlorite); (6) zone located in the central part of the argillitized rocks and consisting of chalcedony and quartz with accumulation of pyrite (melnikovite), cinnabar, and antimonite in veinlets and as impregnations in later generations of chalcedony. The DTA diagrams illustrate the transition from the unaltered rocks to the kaolinized zone. Data are presented on the increase of SiO_2 and water content and decrease of iron, manganese, magnesium, calcium, sodium, and potassium oxides with increase of argillitization. Titanium and aluminum contents are not affected by the argillitization. The

method of molecular volumes is applied to study the effects of the metasomatic reactions. The mobility in this particular case increases from TiO_2 and Al_2O_3 to SiO_2, K_2O, FeO, MgO, Na_2O, CaO, H_2O, and CO_2. The acidity of the ascending leaching solutions was insignificant. This is indicated by the unchanged amount of alumina and by the silicification. The ratio of sodium to potassium suggests that the solutions were richer in potassium than in sodium. Cinnabar and antimonite are present in ore within the zone of complete silicification. Their occurrence in veinlets and as impregnation in late generations of chalcedony indicates the low temperature of solutions. The ore was deposited during the late stages of mineralization. The argillitized rocks are not a direct indicator of ore presence, but they show the intensity of the hydrothermal process and the possibility of ore mineralization.

T. V. Bilibina, Yu. V. Bogdanov, Prospects for Gold Mineralization in the Region of Mugodzhary Mountains (Pp. 104–111).

The Mugodzhary Mountains represent the southern continuation of the Urals. The gold-bearing quartz veins of practical interest occur in the Kumak and Akpan areas. The mineralization of Kumak is associated with a meridional tectonic crushed zone, which is 20 km long. The country rock consists of metamorphic Precambrian complex, Silurian diabases, and Lower Carboniferous metasediments intruded by ultrabasic sills, massifs of metasomatic microcline granites of late Lower Carboniferous age, intrusions of hornblende diorites and dikes of quartz porphyries of Upper Paleozoic age. The gold-bearing ore bodies are located in shear fractures parallel to the strike of the country rock. The ore bodies are up to 100 m long and 12 m thick, and consist of tourmalinized sericite-chlorite quartz schist intersected by gold-bearing veinlets and veins. The first stage of mineralization was characterized by silicification, tourmalinization, and pyritization, accompanied by formation of apatite and wolframite. The second stage of mineralization, which followed minor tectonic movements, was gold-bearing. Quartz, scheelite, carbonates, pyrite, tetradymite, chalcopyrite and calaverite were deposited at this time. The gold mineralization is affiliated with the youngest intrusions of quartz porphyries and diorites. In the ore fields of Akpan and Blak the gold mineralization is located in areas where the porphyries are associated with ultrabasic rocks. Such associations suggest that the sheared zone was tapping deep-seated fractures connected with magmatic chambers.

V. I. Bachaldin, Zonal Distribution of Deposits in the Poladauri Ore Field (Pp. 112–116).

The ore field is located in the Poladauri valley in Southern Georgia. It occupies an area 25 km long and 8 km wide and is associated with an Upper Cretaceous volcanic tuffaceous series attaining a thickness of 3000 m. The oldest tuff formations are located in the southern part of the region and dip to the north. All rocks are intensely altered by hydrothermal processes. The southern zone of mineralization is represented by hematite deposits. In the north they are followed by copper sulfide, lead-zinc, and barite deposits, all arranged in separate zones parallel to that of the hematite deposits. The author suggests that different types of ore formed simultaneously from the same solutions. Iron precipitated when the ascending hydrothermal solutions encountered the vadose waters containing oxygen. Copper, zinc, and lead remained in solution and were precipitated when, at higher horizons, the solutions become cooler.

The lower temperature resulted in dissociation of dissolved hydrogen sulfide molecules which evidently caused the precipitation of sulfides.

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SHORT REVIEWS OF RECENT RUSSIAN BOOKS

Mineraly: Spravochnik. [Minerals: a reference book.] In seven volumes. Vol. I. Pp. 617, figs. 363. Academy of Sciences, Moscow. 1960. Price 35r.

The appearance of the first comprehensive compendium of mineralogy to be compiled within the Soviet Union is an event of considerable importance in the earth sciences. The work is in many respects comparable to the seventh edition of Dana's "System" (the two published volumes of which were translated into Russian in 1950 and 1954 respectively), but it differs from the Western authority principally in paying more attention to Russian studies which were largely unknown in America when the seventh Dana was written. The first of the promised seven volumes sets a high standard and is remarkably free from errors, even in references to Western literature. It covers the native elements and intermetallic compounds, carbides, nitrides and phosphides; arsenides, antimonides, and bismuthides; sulfides; selenides; and tellurides. The edition is 7,000 copies. The second volume will deal with halides and oxides, vols. III and IV with silicates, vols. V and VI with other oxygen compounds, and vol. VII with phase-equilibrium diagrams. For each mineral is given the preferred name, formula, etymology and synonyms, diagnostic characteristics, crystal structure and morphology, chemistry, behaviour on heating, occurrence in nature, alteration, practical significance, means of distinction from similar minerals, and a selected bibliography. The index to vol. I alone lists close on 1,500 mineral names printed both in Cyrillic and Roman characters. The editors-in-chief are F. V. Chukhrov and E. M. Bonshtedt-Kupletskaya, aided by G. P. Barsanov, N. V. Belov, and the late O. M. Shubnikova. Another 19 authors have collaborated in producing the first volume. It seems likely that this new text will rank with Dana as a principal reference work in any internationally-minded mineralogical laboratory.

Oligotzenovye Oolitovye Zheleznye Rudy Severnogo Turgaya i ikh Genezis. [Oligocene oolitic iron ores of northern Turgai and their genesis.] By A. L. YANITZKII. Trudy Inst. Geol. Rudnykh Mestorozhdenii [Trans. Institute for the Geology of Ore Deposits], no. 37. Pp. 219, figs. 82. Academy of Sciences, Moscow, 1960. Price 12r. 60k.

Oolitic ironstone deposits of fluviatile, deltaic-lacustrine, and lacustrine facies are widespread among continental sediments of middle Oligocene age in the northern Turgai and northern Aral'sk districts of Kazakhstan, occupying low-lying river valleys excavated under sub-tropical conditions on the uplifted surface of the marine Palaeogene. The deposits contain the fresh-water mollusc *Pisidium* and an extensive driftwood flora. The largest, Lisakovsk, occurrence extends along a former river valley for a length of 100 km and a breadth of from 2–3 to 7–8 km, the ore seams averaging about 15 m. Intraformational washouts are numerous, demonstrating reworking of the oolitic ores during their deposition. The commonest development is oolith-bearing quartz sandstone containing seams of hydrogoethite oolitic ironstone; other rocks show banded hydrogoethite-chlorite

ooliths in a chlorite-siderite cement. In chemical composition the ironstones exhibit the range 29–73% Fe_2O_3, 0.6–2.5% P_2O_5, 0.6–1.6% CaO, variable SiO_2, and consistently about 0.04% ZnO.

Metody Geologo-Geofizicheskogo Obsluzhivaniya Uranovykh Rudnikov. [Methods of geological-geophysical servicing of uranium mines.] By G. I. PETROV and others. Pp. 217, figs. 67. Atomizdat, Moscow, 1960. Price 8r. 80k.

This unusual work aims at a standardization of the methods of documenting geological, geophysical and assay results at uranium mines and prospects—in borehole and core logging, development, stoping, sampling, estimation of reserves, and so on. Interesting accounts are given of Russian radiometric equipment, and there is a chapter on the use of water analysis for radioactive elements not only in exploration but also in mine assessment.

Voprosy Nakopleniya i Raspredeleniya Tyazhelykh Mineralov v Pribrezhno-Morskikh Peskakh. [The accumulation and distribution of heavy minerals in marine beach sands.] A symposium. Pp. 218. Latvian Academy of Sciences, Riga, 1960. Price 10r. 80k.

A conference on heavy-mineral beach sands held at Riga in May 1959 was attended by 74 geologists from Communist countries, a special interest being shown in the sands of the Baltic coast as a source of ilmenite, rutile, zircon, and (?) monazite. Various resolutions requiring further studies of these deposits were recorded. The proceedings of the conference prints 14 papers, of which the most interesting relate to Baltic and Black Sea sands. The deposits are mostly of low grade, with a relatively high tenor of worthless ferromagnesian minerals.

Magmatizm i Svyaz' s nim Poleznykh Iskopaemykh. [Magmatism and associated mineral deposits.] Pp. 782. Gosgeoltekhizdat, Moscow, 1960. Price 49r. 35k.

A large, well-produced, volume records the proceedings of the second All-Union petrographical congress which met at Tashkent in May 1958 under the presidency of Kh. M. Abdullaev. It comprises about 130 short contributions, mostly papers of 4–6 pages, grouped under the headings (a) general problems of petrography (18 papers); (b) the relationship of mineralization to magmatic activity (30); (c) ultrabasic rocks, kimberlites and associated ore deposits (10); (d) alkalic rocks and associated mineralization (17); (e) metamorphic-metasomatic rocks and ore deposits (19); (f) new data on regional petrology (26); and (g) petrographical methods (6). The diversity of topics is very wide, ranging over most facets of economic, hard-rock, petrography.

C. F. DAVIDSON

UNIVERSITY OF ST. ANDREWS,
SCOTLAND,
April 8, 1961

Die Geologie Mittelamerikas. (The Geology of Central America.) By DR. RICHARD WEYL. Gebrüder Borntraeger., Berlin-Nikolassee 1961. Pp. 226; figs. 61; special maps 6, tables 11. Price, DM 64.00.

This book is the first in a new series entitled "Beiträge zur Regionalen Geologie der Erde" (Contribution to the Regional Geology of the Earth), edited by Pro-

fessor A. Bentz. The editors set the high goal for the series: to give a concise and complex geological description of all the continental regions of the Earth. Their general intention is to offer help to theoretical and practical geological research. These volumes will deal not only with stratigraphic and tectonic aspects, but also with paleogeographic questions, and problems involved in mineral deposits. This new series was preceded by three similar German publications between 1910 and 1944, but all of them remained unfinished.

Dr. Weyl's work, dealing with the continental landbelt of Central America, may deserve special attention in this country. After a physiographic description, two chapters relate the geologic conditions of the northern and southern parts of the region discussed. Whereas the northern unit (Yucatán, Guatemala, Honduras, El Salvador, and northern Nicaragua) is rich in metamorphic rocks and its oldest dated rocks are of Upper Carboniferous age, the southern unit (southern Nicaragua, Cost Rica, Panama) with one exception is devoid of older crystalline rocks. In the south the thick sedimentary series begins only with the Upper Cretaceous.

The fourth, largest chapter of the book, is a valuable, detailed rendering of the abundant Tertiary, Quaternary and Recent volcanism. Chemical analyses (102, of which many are new) show the differing chemical patterns of the volcanic rocks. This is also an impressing contribution to the general and regional volcanology. A short chapter discusses the tectonic conditions and the earthquake-activity.

Many localities contain ore and other mineral deposits in continental Central America, but few are economically significant. Most of the ore deposits are connected with the Upper Cretaceous-Tertiary acidic and intermediate volcanic rocks. These deposits consist partly of contact pneumatolytic iron, lead-zinc, copper, and hydrothermal gold-silver, lead-zinc and partly of antimony and mercury occurrences. Solfataric sulfur deposits, produced by the Quaternary and Recent volcanism, are unimportant compared with the richer gold, silver, antimony, and manganese ore occurrences of the Tertiary volcanism. Gold, platinum, magnetite and ilmenite sands are present in great quantities in the region. The bauxite deposits (Costa Rica, Panama), contrary to the conditions in the Western Antilles, are not yet sufficiently known and are not mined.

A paleogeographical-tectonical summary is given in the seventh chapter. Spanish and English abstracts close the text. The references contain a list of 12 pages of Spanish, English and German geologic literature. More comprehensive stratigraphical correlation tables are lacking; they would enable the readers of this handy and informative work to make a quicker comparison between the different regional units.

ERVIN G. OTVOS

YALE UNIVERSITY,
NEW HAVEN, CONN.,
April 7, 1961

Energy in the American Economy, 1850–1875. By SAM H. SCHURR and BRUCE C. NETSCHERT, with VERA F. ELIASBERG, JOSEPH LERNER, and HANS H. LANDSBERG. Pp. 774; figs. 73; tables 120. Resources of the Future, Inc. Johns Hopkins Press, Baltimore, 1960. Price, $12.50.

This is an economic study of the country's history and prospects. With an annual consumptive energy from all sources and for all users, of 9 tons of coal equivalent per person, this is six times the world average. Consequently the future outlook becomes all important.

Part 1 is an analysis of the history of a century of energy use, from wood to coal, to oil and gas, and to electricity. Part 2 assesses future demains for energy for households, transportation and industry. Part 3 is an investigation of future supply of coal, oil, gas, and waterpower. Aspects of energy consumption are related to Gross National Product, to economic growth, changes in the uses of energy. The future of energy consumption is based on careful economic studies of Gross National Product, population, households, industry, transportation, and government. Under future sources of energy a careful study is made of present and probable future reserves, production costs, and technology.

The authors have drawn upon available literature and scores of individuals, organizations, and utilities and producting companies for data of various kinds.

A beginning chapter is a summary of the general findings. The authors conclude that from 1953 to 1975 there will be a consumption increase of 75% for bituminous coal, − 30% for anthracite, 86% for oil, 196% for natural gas liquids, 107% for natural gas, and 121% for hydropower, and 211% for energy consumed as electricity. They conclude also that domestic availability by 1975 will be large enough to satisfy consumption.

The work is a very thoughtful survey of present and future consumption and available supply of energy sources combined with economic and technologic growth. It is an invaluable reference source and is bound to be widely quoted in the future.

Grundlagen der Angewandten Geophysik fur Geologen. By HERMANN REICH. Pp. 236; figs. 1121. Akademische Verlagsgesellschaft, Leipzig, 1960. Price, DM 26.

This general reference and textbook covers the broad field of geology. The first section covers the physical properties of minerals and rocks. A second section deals with the various geophysical methods, the instruments used, and the interpretation of results. This section is just about the same as in the other standard books on geophysics, except that it is a little briefer. The third section takes up the application of geophysical measurements and geologic problems. It treats of mapping by magnetic, electric, gravimetric and radioactive and thermal mapping, and well logging, with reference to individual examples and different geologic columns.

The book is intended for readers in German and is less complete than other books in English.

Geologie Stratigraphique. Fifth edition. By MAURICE GIGNOUX; *addendum* by LEON MORET. Pp. 760; figs. 155. Masson et Cie, Paris, 1960.

This well known book retains the body of material of the fourth edition, but newer information since 1951 has been brought up to date by M. Moret. The Quaternary has been particularly augmented and much newer material regarding Western Europe and North Africa has been added.

The same arrangement as in the last edition has been followed—starting with the Precambrian through the Quaternary. Under each is taken up the distribution, fauna, flora, and detailed stratigraphy illustrated in typical areas (mostly in Europe), facies changes, and paleography. The final chapter in the Quaternary considers also glaciation, history of human industries, post-glacial time, and the history of Alpine glaciation. The addendum contains an extensive recent bibliography.

As with the last edition this volume will be an excellent reference work.

BOOKS RECEIVED

ERIC S. CHENEY AND ROGER L. AMES

Soils in Canada. Edited by R. F. LEGGET. Pp. 229. Univ. of Toronto Press, 1961. Price, $6.50. *This work on geological, pedological, and engineering studies by 20 contributors resulted from a symposium at Queen's University in 1960. Treats of soils in the various areas of Canada and engineering applications.*

A Hole in the Bottom of the Sea. WILLARD BASCOM. Pp. 352. Doubleday & Co., New York, 1961. Price, $4.95. *A popular story of the Mohole Project; its objectives, problems, equipment, geophysics of the crust, oceans, magnetism, heat and pressure, and drilling methods.*

Black Gold—The Story of An Oil Pioneer. A. BEEBY-THOMPSON with an introduction by Herbert Hoover. Pp. 544. Doubleday & Co., New York, 1961. Price, $5.95. *A biography by a renowned petroleum geologist and engineer dealing with his activities in many of the oil regions of the world and giving the history of their development.*

The World of Geology. Edited by L. DON and FLORENCE J. LEET. Pp. 262; many illustrations. Price, $4.25. *Nineteen chapters by different authors covering origin of the earth, life, evolution, the atmosphere, oceans, ice, the earth's interior, volcanism, erosion, groundwater, rocks and minerals, and mountains.*

Professional Manpower and Education in Communist China. LEO A. ORLEANS. Pp. 260. National Science Foundation, Washington, D. C., 1961. Price, $2.00. *Covers education, science and technology, professional manpower, population, sample curriculum and examinations, scientific research institutes.*

Geology of Ben Nevis and Glen Coe, 2nd Edit. E. B. BAILEY, H. B. MAUFE, and others. Pp. 307, figs. 41, tbls. 4, pls. 13. Her Majesty's Stationery Office, Edinburgh, 1960. Price, £1 15s. *Since the publication of the first edition (1915) the discovery of current bedding in quartzite members has indicated the tops of beds and the correct stratigraphic succession in recumbent folds and schists.*

The Mining Journal—Annual Review, 1961. Pp. 376. The Mining Journal Ltd., London. Price, 25/. *This thick, comprehensive review covers all of the various metals and minerals of industry; technical progress in mineral exploration, geological surveys, mining, beneficiation, and metallurgy; and a review of the world's mining fields in 1960, arranged according to countries, or areas, or continents. A section is devoted to the progress of individual companies. An excellent review.*

Geologic map, scale 1/200,000, Apaiqua, S.E. sheet. Price, $1.00. British Guiana Geological Survey, Georgetown.

An Annotated Bibliography of California Cretaceous Microfossils. J. J. GRAHAM. Pp. 43; figs. 2. Price, $1.00. Special Rept. 66, California Div. of Mines, San Francisco, 1961. *A brief history of the literature precedes the discussion of 180 titles from 1891 to 1960.*

Studies of Ordovician Algae. J. H. JOHNSON and O. A. HØEG. Pp. 120; pls. 39; figs. 5; tbls. 2. Price, $2.00. Quarterly of the Colorado School of Mines, Vol. 56, No. 2, Golden, 1961. *In Part 1 the senior author reviews the available data, presents the fundamental ideas of classification, and briefly describes the various genera. In Part 2, Høeg reviews the more important genera of Norway and the problems connected with them.*

Annual Report of the Geological Survey Department for 1960. L. M. BEAR. Pp. 47. Cyprus Geological Survey, Nicosia, 1961. *Articles on the geomorphology of Cyprus and a bibliography of Cyprus geology are included in this report.*

Geological Survey Department Annual Report for 1960. Pp. 10; map, scale 1/20 miles. Price, 1s. 6d. Council Paper No. 5 of 1961, Colony of Fiji. *Several copper prospects have been mapped and drilled.*

Notas 1, 1a and 2, 2a, Studio Statistico del Mercantili and Studio Statistico di Campioni Prelevati Nel Giacimento. A. BIANCHINI, I. SALVADORI, and P. ZUFFARDI. Pp. 50; pls. 23; tbls. 4; and Pp. 52; pls. 30; tbls. 4. Rendiconti della Societa Mineralogica Italicano, Vol. 16, Pavia, 1960. In Italian. *Reports including the silver, antimony, tin, and bismuth tin content of the lead ores.*

Geological Survey, Federation of Malaya, Airborne Magnetometer and Scintillation Counter Survey, by W. B. AGOCS, with geology by J. R. PATON and interpretations by J. B. ALEXANDER. Bull. 1.1, 1.2; 1.5, 1.6, Ipoh, 1968. Price, $5.00 Malayan per volume. *Areas: Perak, Salangor; Trengganu and Pahang; Johore and Malacca; Kedar and Perlis. Geology, mineral deposits, surveying, interpretations and maps.*

Production Statistics—Official Oil in North Dakota Second Half 1960. Pp. 109. Price, $2.00. Grand Forks, 1961. *This report represents the official publication of production data for 91 oil pools.*

Annual Report of the Department of Geological Survey for 1960. Pp. 9. Price, 2s. Northern Rhodesia, Geological Survey, Lusaka, 1961. *Contains a list of publications issued during 1960.*

New York Geological Survey—Albany, 1961.

Bull. GW-43. Ground-Water Resources of Dutchess County, New York. E. T. SIMMONS, I. G. GROSSMAN, and R. C. HEATH. Pp. 57; figs. 5. Maps 3, scale 1/1.5 miles. *The ground water use for the county is estimated to be about 7 million gallons per day with no appreciable depletion.*

Bull. GW-44. Ground-Water Levels and Their Relationship to Ground-Water Problems in Suffolk County, Long Island, New York. J. F. HOFFMAN and E. R. LUBKE. Pp. 21; pls. 2; figs. 6; tbls. 3. *The aquifers are two late Cretaceous formations and the unconsolidated Pleistocene deposits. The ground water supply is adequate for future population growth.*

Union of South Africa Department of Mines—Pretoria, 1960.

Sheet 253. The Geology of the Bitterfontein Area, Cape Province. H. JANSEN. Pp. 84; pls. 13. Price, 10s. In English. *The area is underlain by the Malmsbury formation of Precambrian age. This formation has metamorphosed and granitization has taken place on a large scale.*

Blad 241. Die Geologie Van Die Gebied Om Neiuwoudtville, Kaapprovinsie. J. W. VON BACKSTROM. Pp. 47; pl. 1; figs. 11. Price, 6s. English summary. *The bedrock ranges from the Malmsbury to Karroo formations. Gypsum is the only mineral that occurs in economic quantity.*

Sheet 22. The Geology of the Country North of Nelspruit. H. N. VISSER and W. J. VERWOERD. Pp. 117; pls. 18; figs. 19. Map 1. Price, R1.45. *Gold-quartz-pyrite veins constitute the ore deposits of the Transvaal gold field. The irregular distribution of ore grade mineralization has frustrated large scale mining.*

Blad. 4. Die Geologie Van Rustenburg en die Omliggende Bebied. J. W. VON BACKSTROM. Pp. 92; figs. 15; folders 2. Price, R1.20. English summary. *Diamonds, platinum, palladium and iron are the most important mineral products of the Rustenburg area.*

Memoir 49. The Geology of the Orange Free State Gold-Field. C. B. COETZEE. Pp. 188; figs. 11; folders 10. Maps 2, scale 1/100,000. Price, R2.25. *Production from the Orange Free State gold field amounted to 5.5 million ounces of gold and 216 million pounds of uranium oxide.*

Southern Rhodesia Geological Survey—Salisbury, 1960–1961.

Bull. 47. The Great Dyke of Southern Rhodesia. B. G. WORST. Pp. 234; pls. 23; figs. 5; tbls. 41. Geologic map of the Great Dyke of Southern Rhodesia, 9 sheets, scale 1/100,000. *A detailed discussion of the general and economic geology, including the vast chromite deposits of the Great Dyke. The author concludes that the Great Dyke was emplaced by successive inflows of magma, and is not a dike but the remains of four lopoliths which were formed in a straight line. The four complexes were preserved in a grabon so that erosion has produced the dike outline.*

Mining in Southern Rhodesia. 1960 Annual Reports of the Southern Rhodesia Government. Pp. 58. Price, 10'6.

U. S. Geological Survey—Washington, D. C., 1960–1961.

Bull. 1083-E. Anomalous Remanent Magnetization of Basalt. ALLAN COX. Pp. 29; figs. 12. Price, 20 cents. *Lightning is probably the most common cause of anomalous magnetization in the lava flows of Idaho.*

Bull. 1084-H. An Evaluation of Whole-Order, 1/2-order, and 1/3-order Reporting in Semiquantitative Spectrochemical Analysis. PAUL R. BARNETT. Pp. 23; figs. 3; tbls. 6. Price, 15 cents. *The results of 507 spectrochemical determinations in 63 samples are evaluated by the percentage of successive assignments to the correct range and by calculation of the logarithmic standard deviation.*

Bull. 1084-I. A Spectrochemical Method for the Semiquantitative Analysis of Rocks, Minerals, and Ores. A. T. MYERS, R. G. HAVENS, and P. J. DUNTON. Pp. 22; fig. 1; tbls. 11. Price, 15 cents. *A visual comparison method for semiquantitative spectrochemical analysis of a power by d-c arc technique is described.*

Bull. 1089-A. Geology of the Alvord Mountain Quadrangle, San Bernardino County, California. F. M. BYERS, JR. Pp. 71; pls. 6; figs. 2; tbls. 4. 1 map, scale 1/62,500. *Part of a general appraisal of the mineral resources of the Mohave Desert region.*

Bull. 1089-B. Geology of the Rogers Lake and Kramer Quadrangles, California. T. W. DIBBLEE, JR. Pp. 66; pls. 3; figs. 4. Map, scale 1/62,500. *The rock of the area are divisible into pre-Tertiary crystalline rocks; Tertiary volcanic, pyroclastic, and sedimentary rocks; and Quarternary alluvial sediments. Unwarping and subsequent erosion have produced low, broad hills and basins filled with alluvium.*

Bull. 1098-A. Geochemical Studies in the Coeur d'Alene District, Shoshone County, Idaho. VANCE C. KENNEDY and S. WARREN HOBBS. Pp. 55; pls. 7; figs. 20; tbls. 7. Price, $1.25. *Semiquantitative chemical analyses were made principally for copper, lead, and zinc in soils collected near veins and in soils collected at a distance from known veins.*

Bull. 1098-B. Geochemical Prospecting Abstracts, January 1955–June 1957. ELLEN L. MARKWARD. Pp. 104. Price, 35 cents. *A compilation, worldwide in scope, of abstracts of papers on geochemical prospecting, exclusive of petroleum.*

Bull. 1101. Vanadium-Uranium Deposits of the Rifle Creek Area, Garfield County, Colorado. R. P. FISCHER. Pp. 52; pls. 10; figs. 8; tbls. 3. Map, scale 1/31,600. *Ore bodies are slightly discordant with the major bedding and some mineral zonation. An alteration zone at the top of the Chenle formation offers a prospecting guide.*

Bull. 1111-E. Stratigraphy of the Moose River Synclinorium, Maine. A. J. BOUCOT. Pp. 35; figs. 3. Map, scale 1/250,000. *Description of the early Paleozoic rocks in west-central Maine, with emphasis on those of Silurian and Devonian age.*

Bull. 1115. Bibliography of North American Geology, 1958. RUTH R. KING and others. Pp. 592. Price, $2.00. *This bulletin consists of an author bibliography and a subject index.*

Bull. 1116-D. Geophysical Abstracts 183 October–December 1960. J. W. CLARKE, D. B. VITALIANO, VIRGINIA S. NEUSCHEL, and others. Pp. 638. Price, 40 cents. *Abstracts from current, worldwide literature which pertains to the physics of the solid earth and geophysical exploration are arranged by subject.*

Prof. Paper 303-D. Geology of the Shaviovik and Sagavanirktok Rivers Region, Alaska. A. S. KELLER, R. H. MORRIS, and R. L. DETTERMAN. Pp. 53; pls. 6; figs. 7; tbl. 1. Map, scale 1/125,000. *The first of a series of reports of the structure and stratigraphy of the Arctic slope now being mapped for petroleum possibilities. Mississippian, Permian, Triassic, and Cretaceous beds are possible petroleum reservoirs.*

Prof. Paper 311. Geology of Northeasternmost Tennessee. P. B. KING, H. W. FERGUSON, and WARREN HAMILTON. Pp. 136; pls. 19; figs. 27. Map, scale 1/48,000. *A classic report on the stratigraphy, metamorphic petrology, and, especially, the structure of a classic area of Schist sheets. Of the Precambrian and Middle Ordovician deformations three periods of thrusting are recognized in the main, post-Mississippian orogeny.*

Prof. Paper 339. Tertiary and Quaternary Gastropoda of Okinawa. F. STEARNS MACNEIL. Pp. 113; pls. 21; figs. 17. Price, $2.50. *A comparison of the late Miocene, Pliocene and Pleistocene Gastropoda of Okinawa with related faunas of East Asia together with a résumé of the geologic setting of the fossiliferous deposits.*

Prof. Paper 347. Geomorphology and Forest Ecology of a Mountain Region in the Central Appalachians. J. T. HACK and J. C. GOODLETT. Pp. 66; pls. 7; figs. 31; tbls. 49. *Rare floods, such as violent cloudbursts, are thought to occur frequently enough to be the major erosive agent and an important element in the life history of the forest.The present topography and distribution of vegetation are not indicative of peneplanation or progressive biological succession.*

Prof. Paper 358. Primary Textures and Mineral Association in the Ultramafic Zone of the Stillwater Complex, Montana. E. D. JACKSON. Pp. 106; figs. 92; tbls. 10. Price, $1.00. *The petrographic features and origin of the layered chromites, bronzitites, and harzburgites in the lower part of the Stillwater complex.*

Prof. Paper 366. Ash-Flow Tuffs: Their Origin, Geologic Relations and Identification. C. S. Ross and R. L. SMITH. Pp. 81; figs. 98. *A discussion of*

the development of the concept of the origin of ash flow tuffs. Gives detailed descriptions of their character and mode of occurrence; presents criteria for Sheir recognition; considers their distribution and consolidation.

Prof. Paper 373. Aerial Photographs in Geologic Interpretation and Mapping. R. G. RAY. Pp. 230; figs. 116. Price, $2.00. *The use of aerial photographs to obtain qualitative and quantitative geologic information, and instrument procedures employed in compiling geologic data from aerial photographs. Many stereo pair are included for instructional purposes making the report valuable for classroom as well as for field office use.*

Prof. Paper 374-A. Upper Eocene and Oligocene Larger Foraminifera from Viti Levu, Fiji. W. STORRS COLE. Pp. 6; pls. 3; fig. 1; tbl. 1. *Illustrations of first Eocene and Oligocene fossils from Fiji, and their occurrence in surrounding areas.*

Prof. Paper 374-B. Joints in Precambrian Rocks, Central City-Idaho Springs Area, Colorado. J. E. HARRISON and R. H. MOENCH. Pp. 14; figs. 10; tbl. 1. Price, 20 cents. *Each of the major Precambrian intrusive masses has primary joints and joints can be related to two periods of Precambrian deformation and probably Laramide arching.*

Water-Supply Paper 1369-B. Energy Losses Associated With Abrupt Enlargements in Pipes. C. E. KINDSVATER. Pp. 22; pls. 3; figs. 9; tbls. 5. Price, 25 cents. *Experimental investigation of the flow of water through abrupt, concentric enlargements in circular pipes indicates that the conventional method of computing the energy loss in pipes is adequate for practical use.*

Water-Supply Paper 1460-I. Effect of Irrigation Withdrawals on Stage of Lake Washington, Mississippi. E. E. HARBECK, JR., H. G. GOLDEN, and E. J. HARVEY. Pp. 29; figs. 16; tbls. 2. Price, 20 cents. *Withdrawals are partly balanced by increased seepage into the lake when the groundwater level is high; thus, the lake level is lowered by an amount less than the amount withdrawn.*

Water-Supply Paper 1491. Geology and Groundwater Features of the Butte Valley, Siskiyou County, California. P. R. WOOD. Pp. 150; pls. 3; figs. 7; tbls. 13. *Bedrock in this area consists of Tertiary volcanics of the Cascade Range and Plio- and Pleistocene sediments. Basalt flows and alluvium are the chief aquifers.*

Water-Supply Paper 1498-A. Flume Studies Using Medium Sand (0.45 mm). D. B. SIMONS, E. V. RICHARDSON, and M. L. ALBERTSON. Pp. 75; figs. 28; tbls. 2. *This study of fluvial mechanics, specifically roughness in alluvial channels, is based on data collected by using a recirculating, rectangular flume of adjustable slope.*

Water-Supply Paper 1498-C. Depth-Discharge Relations of Alluvial Streams —Discontinuous Rating Curves. D. R. DAWDY. Pp. 16; figs. 11; tbl. 1. Price, 15 cents. *A quantitative approach to the problem of stream rating shows that a discontinuity occurs on the depth-discharge relation of many alluvial streams.*

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SCIENTIFIC NOTES AND NEWS

WILLIAM P. HEWITT has been appointed by the Board of Regents of the University of Utah as Director of the Utah Geological and Mineralogical Survey. He has also been appointed Professor in the Department of Geology, University of Utah, where he will serve half-time and teach courses in economic geology. He succeeds ARTHUR L. CRAWFORD, and assumed office on July 1.

JOHN H. MELVIN, formerly General Manager of the Pennsylvania Drilling Company, and onetime State Geologist of Ohio, has assumed practice as a consulting geologist with headquarters in Pittsburgh.

The Department of Geology and Bureau of Economic Geology of The University of Texas and the Instituto de Geologia of La Universidad Nacional Autonoma de Mexico have recently signed a cooperative agreement for geologic research in Mexico.

Graduate students at The University of Texas of both United States and Mexican citizenship will undertake research problems in Mexico. The Instituto de Geologia will designate problem areas, cooperate in supervision, furnish field assistance, materials and supplies, help to defray field expenses, and provide a Spanish language vehicle for publication. In addition, the Instituto will recommend Mexican candidates for graduate study at The University of Texas and assist in financing their graduate studies. The Department of Geology and Bureau of Economic Geology will direct the geologic research in Mexico, supervise the field work and provide financial assistance for Mexican graduate students through scholarships, fellowships, and assistantships.

A. K. SNELGROVE, Head of the Department of Geology and Geological Engineering at the Michigan College of Mining and Technology, has been appointed as a Fulbright lecturer in economic geology at the University of Sind, Nyderabad, West Pakistan, for 1961–62. In 1953–54 Dr. Snelgrove held a similar post at the University of Hong Kong.

The Sociedad Geologica Boliviana was organized in March 1961 with a membership of approximately seventy geologists. GUSTAVO DONOSO, Director of the Departmento Nacional de Geologia, is President, and HENRY C. MEYER is Secretary. The first number of a mimeographed news letter entitled "Noticiero de la Sociedad Geologica Boliviano" was issued in May. The Society's address is Edificio Minminas, 4° Piso, Casilla 2729, La Paz.

The Council of the Institution of Mining and Metallurgy, London, have announced the following awards: The Gold Medal of the Institution for 1960 has been awarded to the RT. HON. LORD BAILLIEU; Honorary Membership of the Institution has been conferred on Professor CECIL WILLIAM DANNATT, Past-President; The Consolidated Gold Fields of South Africa Limited' Gold Medal for 1959–60 has been awarded to ROBERT NELSON PRYOR for his paper entitled "Mining of Cupreous Stockwork Ores at Rio Tinto, Spain"; The Consolidated

Gold Fields of South Africa, Limited' Premium of Forty Guineas for 1959–60 went to MARTIN LAWRENCE FITZGERALD for his paper entitled "Metallurgical Accounting and Control."

The Massachusetts Institute of Technology is recipient of a lectureship established by the estate of the late Irving Ballard Crosby in memory of his father, William Otis Crosby. The first holder of the lectureship will be Dr. JOSEPH L. GILLSON who will give a two-term series of lectures next year on industrial minerals.

The Society of Exploration Geophysicists will sponsor thirty scholarships for studies in geophysics during 1961–62. More than $26,000 in scholarships will be awarded this year. Of this total, $2,000 will be awarded in foreign scholarships.

GEORGE A. THIEL, Chairman of the Department of Geology at the University of Minnesota, Minneapolis, Minnesota, retired at the close of the academic year on June 30. His replacement for the chairmanship is Dr. PRESTON CLOUD, JR. of the U.S. Geological Survey, who will assume the duties of the position at the beginning of the fall term at the University.

BRUCE C. HEEZEN, Assistant Professor of Geology in Columbia University was in Russia in June where he lectured as an official guest of the Academy of Sciences of the U.S.S.R. at the Institute of Oceanology and other of the Academy's institutes.

A Columbia University joint anthropology-geology expedition will explore the Nubian sector of the Nile Valley in a search for the missing link between the very primitive man of Africa and the ancient man of Europe. The leaders of the expedition will be Dr. RALPH SOLECKI, Associate Professor of Anthropology at Columbia, and Dr. RHODES W. FAIRBRIDGE, Professor of Geology at Columbia.

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CONTENTS

Part I

FOREWORD ii
ECONOMIC GEOLOGY ..... *Alan M. Bateman* 1
METALLOGENETIC PROVINCES AND EPOCHS ..... *F. S. Turneaure* 38
THERMAL SPRINGS AND EPITHERMAL ORE DEPOSITS ..... *Donald E. White* 99
THE CLASSIFICATION OF ORE DEPOSITS ..... *James A. Noble* 155
STRUCTURE OF HYDROTHERMAL ORE DEPOSITS ..... *H. E. McKinstry* 170
THE ZONAL THEORY OF ORE DEPOSITS ..... *Charles F. Park, Jr.* 226
TEMPERATURES IN AND NEAR INTRUSIONS ..... *T. S. Lovering* 249
SYNTHETIC MINERALS ..... *W. A. Weyl* 282
HYDROTHERMAL ALTERATION AS A GUIDE TO ORE ..... *George M. Schwartz* 300
OXIDATION OF COPPER SULFIDES AND SECONDARY SULFIDE ENRICHMENT ..... *Charles A. Anderson* 324
METHODS AND PROBLEMS OF GEOLOGIC THERMOMETRY ..... *Earl Ingerson* 341
SEDIMENTARY DEPOSITS OF RARE METALS ..... *Konrad B. Krauskopf* 411
ORIGIN OF URANIUM DEPOSITS ..... *V. E. McKelvey, D. L. Everhart and R. M. Garrels* 464

Part II

ENGINEERING GEOLOGY—A FIFTY YEAR REVIEW ..... *Robert F. Legget* 534
INFLUENCE OF GEOLOGICAL FACTORS ON THE ENGINEERING PROPERTIES OF SEDIMENTS ..... *Karl Terzaghi* 557
RECENT DEVELOPMENTS IN CLAY MINERALOGY AND TECHNOLOGY ..... *Ralph E. Grim* 619
PROPERTIES OF CALCIUM AND MAGNESIUM CARBONATES AND THEIR BEARING ON SOME USES OF CARBONATE ROCKS ..... *D. L. Graf and J. E. Lamar* 639
THE QUANTITATIVE APPROACH TO GROUND-WATER INVESTIGATIONS ..... *John G. Ferris and A. Nelson Sayre* 714
TIME OF PETROLEUM ACCUMULATION ..... *A. I. Levorsen* 748
COAL PETROLOGY ..... *C. E. Marshall* 757
THE USE OF GAMMA RAY MEASUREMENTS IN PROSPECTING ..... *William L. Russell* 835
ECONOMIC APPLICATIONS OF PALEOCOLOGY ..... *Samuel P. Ellison* 867
GEOPHYSICS APPLIED TO PROSPECTING FOR ORES ..... *Louis B. Slichter* 885
MINOR ELEMENTS IN SOME SULFIDE MINERALS ..... *Michael Fleischer* 970
THE STUDY OF PEGMATITE DEPOSITS ..... *Richard H. Jahns* 1025–1130

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